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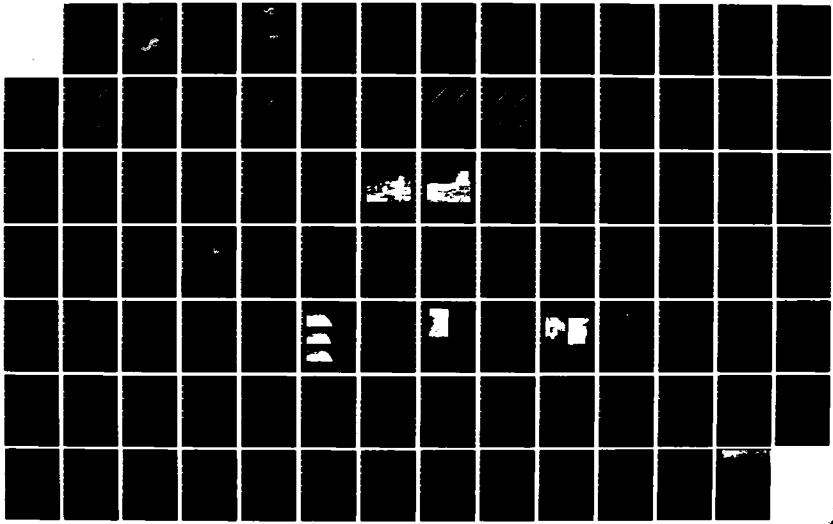

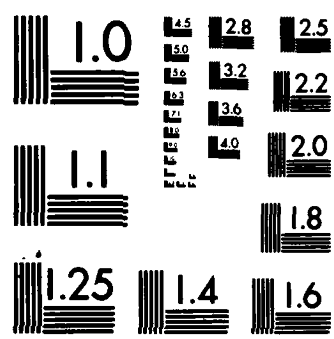

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A STUDY OF EXTREME WAVES AND THEIR EFFECTS ON SHIP STRUCTURE

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1983

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Ship Structure Committee

An Interagency Advisory Committee
Dedicated to Improving the Structure of Ships

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13 JAN 1984

SR-1281

This report represents one of the technical community's earliest efforts to describe, quantify, catalogue and assess the characteristics of extreme waves. It is intended that future efforts in this area will focus on recreating the various types of extreme waves in model tanks in order that each ship design could be evaluated for its own response.

This report is of value not only to the technical community, but also to ship operators who are interested in avoiding these extreme waves.

Clyde T. Lusk, Jr.
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

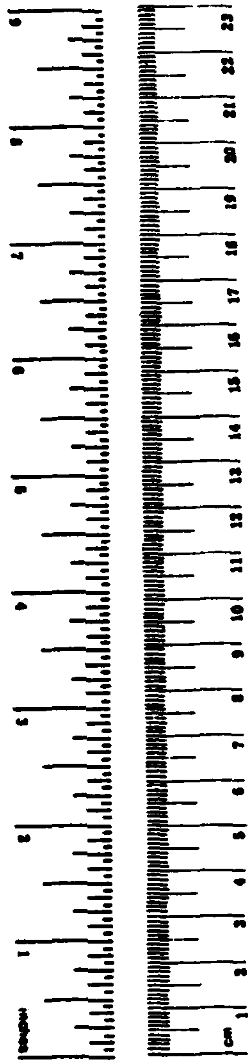
A-1

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

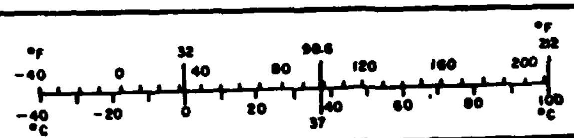
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

This report is the result of a project to determine the possibility of a ship encountering some kinds of extreme waves and to understand the significance of such encounters in ship structural design. Previous studies indicated that certain large waves, measured during Hurricane Camille, might be characterized as non-Gaussian. Waves of similar time-domain description had previously been found to cause ship damages during winter storms.

Interviews with ship masters and officers furnished additional important characterizations of these waves, as well as indications of the synoptic weather conditions which were involved. A survey of heavy-weather damage information from U.S. Coast Guard records was conducted to evaluate general trends of heavyweather damage to ships. A preponderance of damage is attributed to local wave loadings. Selected cases of ship damage and severe hull girder stressing ~~are~~ examined in relation to the types of extreme waves reported to have been encountered, or believed to have been encountered, based in part upon prevailing synoptic weather conditions.

(Continued on next page)

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16. Abstract (Continued)

A tentative characterization of large non-Gaussian waves is provided. Recent developments in nonlinear wave mechanics are reviewed to help explain the origin and propagation of these waves. Current studies of the synoptic development of winter storms are also examined to identify wind field characteristics which appear to be related to the development of "rogue" waves.

A program of research is recommended to develop the environmental data base and analytical methods associated with achieving a better understanding of the characteristics of extreme waves, the associated synoptic weather conditions, and the effects of extreme waves on ships.

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1.0 INTRODUCTION

Ship structure is designed to withstand local and overall hull girder loadings which are based to a considerable degree on requirements of classification societies, design manuals, etc. These requirements typically are developed from past experience with similar ships and do not originate from a "first principles" derivation of seaway loadings. As a result, assurances of ship structural integrity in seaways of extreme proportions tend to be implicit rather than explicit. Occasionally ship heavy-weather damages testify to the fact that a rational understanding of the nature of the more extreme waves encountered in storms and of their potential effect on ship structure would be desirable. It is to this ultimate end that the present study is directed.

The specified objectives and tasks of the study are as follows:*

"A. Objective

The objective of this project is to determine the possibility of a ship encountering some kinds of extreme waves and to understand the significance of this in ship structural design."

"B. Background

Numerous ships have been severely damaged or lost through structural failure caused by encounter with an episodic wave of extreme height and force. There is need of better understanding of the behavior of ship's hull structures under such conditions. Research is underway on the ultimate strength of ships structural elements under collapse loads. However, there is now no understanding of how these extreme waves load the ship's structure. It is important to know whether the critical problem is one of hull girder failure, extreme bow slamming, "green water" on deck, superstructure damage, or some other phenomenon."

"C. Work Scope

The following tasks are to be considered in meeting the objective:

(a) Survey published data worldwide about these occurrences.

(b) Consult classification societies, marine insurers and salvors, owners, government agencies and any other sources of unpublished data on these losses, such as Lloyd's of London Shipping Information Service. Determine need for and schedule personal visits with officials in the United States and overseas.

(c) Conduct visits and prepare trip reports.

(d) Classify the data gathered by geographical location, incident environmental condition, type vessel, type damage, loss of life, financial loss, and environmental damage.

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*From contract work statement.

(e) Identify the most common and the most severe forms of structural failure which have occurred in the past from extreme wave loading.

(f) Analyze and discuss the data to determine the most significant circumstances surrounding these cases.

(g) Recommend a program of future research."

As in the case of other research investigations that are somewhat exploratory in nature, knowledge gained during the course of the study has suggested that certain aspects be given more emphasis, and others less, as the investigation progressed. In this instance the study of published worldwide data was confined mainly to a survey of U.S. Coast Guard Reports of Vessel Casualty or Accident (Form CG-2692) because they constituted a useful and representative data base and because it soon became apparent that the study of selected damage incidents for which relatively detailed information was available was more likely to permit attainment of the basic study objective.

Interviews of ship's officers with considerable at-sea experience, which was a speculative undertaking at the outset, ultimately had a major effect on the results of the study. This was also true of the decision to correlate damage incidents with synoptic weather information. As a result of this particular decision, the analysis of data "gathered by geographical location" was deemphasized since synoptic weather studies were found to provide a better understanding of the influence of geographic location than damage trends per se.

The findings of the study are of a circumstantial nature to a considerable degree, there being very little measured seaway, wind, and ship response information for the synoptic storm conditions suggested here to be of critical importance. The research projects that are recommended are nevertheless believed to be of a substantial nature and justified by the findings of the study, even though these findings are largely circumstantial at this time.

2.0 BACKGROUND AND APPROACH

The approach taken to the conduct of this study has been strongly influenced by development of the half-cycle matrix (HACYM) method of random data analysis and its application to wave data obtained during Hurricane Camille.[1]* Because of their relevance, these developments and some of the associated findings regarding Hurricane Camille wave data are first reviewed.

2.1 Half-Cycle Analysis of Wave Data

As a result of developments related originally to the analysis of broadband fatigue load data, the half-cycle method of analyzing random time-series data has evolved.[2] The procedure and some of its basic characteristics are as follows:

Figure 1 illustrates the basic procedure for half-cycle counting of time-series data and for entering individual counts into the associated data matrix, or HAYCM.

*References are listed beginning on page 62.

The signal is first banded into uniform data intervals on either side of the reference data level. Each data interval has been given a data interval designator (+J through -J) for identification. Whenever a data peak (maximum or minimum) occurs, it is identified with a particular data interval designator. In Figure 1, the half-cycle (1) has a first peak of -B and a second peak of +E; as a result, it is entered into the HACYM data bin corresponding to a first peak -B and second peak +E. (Note: in Figure 1 the half-cycle identifiers (1) through (6) have been entered to illustrate the procedure. Normally the data bin would contain a number which correponds to the number of times the data sample in question had half-cycle excursions corresponding to that particular data bin.) This procedure is repeated for other half-cycle excursions such as (2) through (6) until all of the data have been processed.

The signal employed here illustrates certain basic features of the dispersion pattern of half-cycle counts within the HACYM. First, matching half-cycles will fall into data bins symmetrically disposed on either side of the full diagonal, i.e., about the diagonal formed by the darkened squares. Thus, if the HACYM were folded along the null diagonal, the data bins containing matching half-cycles would fall one upon the other. The half-cycles (2) and (3) would then fall on one another as would (1) and (4). Second, a half-cycle count located on the reference level diagonal, designated here by the straight line running from the upper left to the lower right corner of the HACYM, corresponds to a half-cycle excursion such as (5), which is symmetrical about the reference data level. Third, the up-going half-cycles (1), (3), and (5) all appear on the right hand side of the null diagonal, while the down-going half-cycles (2), (4), and (6) all appear to the left of the null diagonal.

Figure 2 has been prepared to illustrate the significance of the location of a half-cycle count within the HACYM. In this figure, the half-cycle excursion previously designated (1) has been characterized in terms of its mean value and its amplitude which, in this case, are 1 1/2 and 3 data intervals, respectively. It will be seen in the HACYM of Figure 2 that the location of a half-cycle count with respect to the null diagonal is a direct measure of the amplitude of the half-cycle excursion, while the location with respect to the reference level diagonal is a direct measure of its mean value. Half-cycle counts having positive means fall to the right of the reference level diagonal and vice versa.

If, following the processing of a large amount of random data, a three-dimensional figure were to be constructed such that the ordinate at each data bin corresponded to the number of half-cycle counts in the data bin, and if the figure were normalized to contain unit volume, the individual ordinates would then correspond to the joint probability of a particular mean value occurring in combination with a particular amplitude. All wave data processed to date have shown a tendency toward symmetry about the null diagonal of the HACYM.

Using an analytical approach developed by Yang,[3] Andrews[4] recently analyzed an idealized narrow-band Gaussian process in HACYM format. One of the band-limited white noise spectra employed in the analysis is shown in Figure 3 together with the resulting distributions of half-cycle counts for a particular number of half-cycle events, Figure 4. The principal characteristics of the dispersion pattern are: (a) symmetry about the diagonals of the HACYM and (b) a Rayleigh distribution of peak counts $p(x) = X/C^2 \exp(-X^2/2C^2)$ where $C^2 = 1/2\ \Sigma X^2{}_i$ for the associated

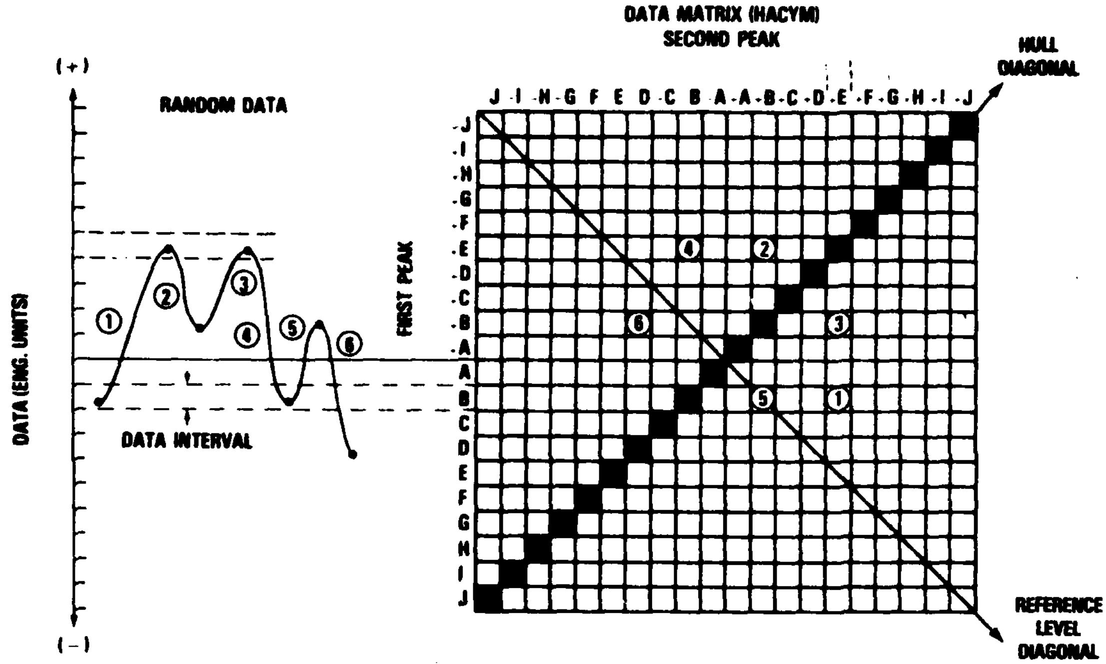

Figure 1 - Half-Cycle Counting of Random Time-Series Data

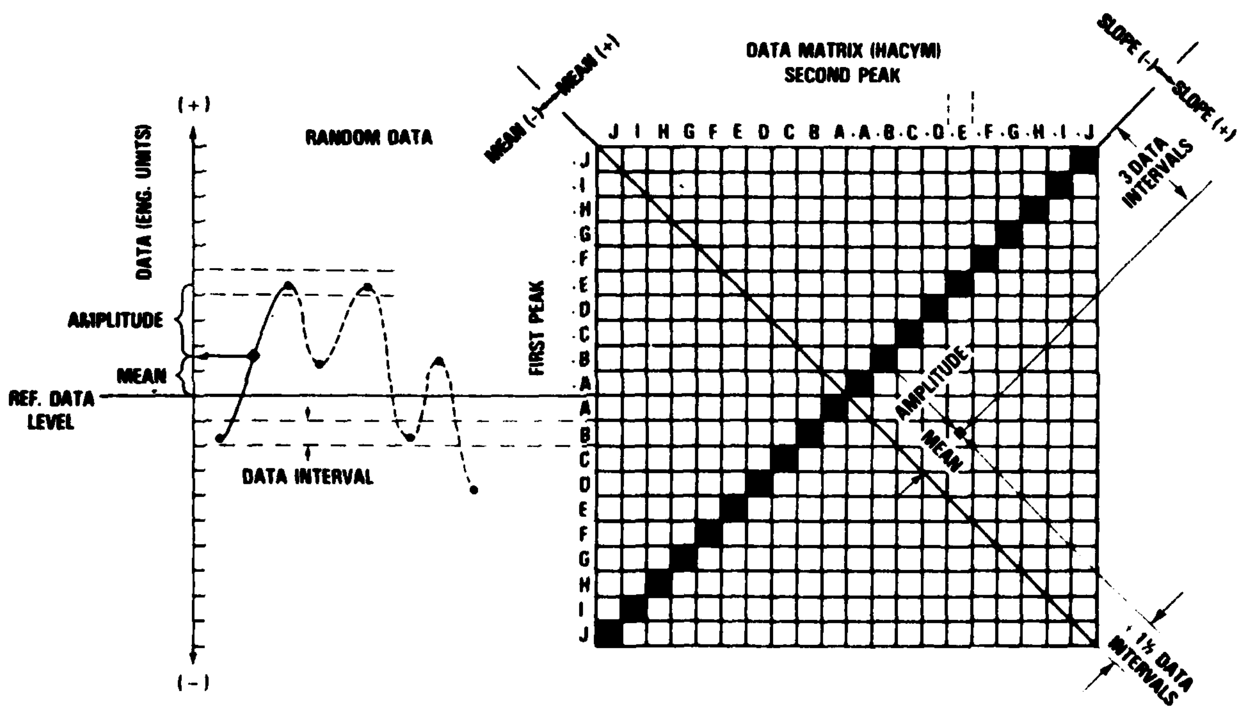

Figure 2 - Characterization of Half-Cycle Data Excursions Within the Half-Cycle Matrix

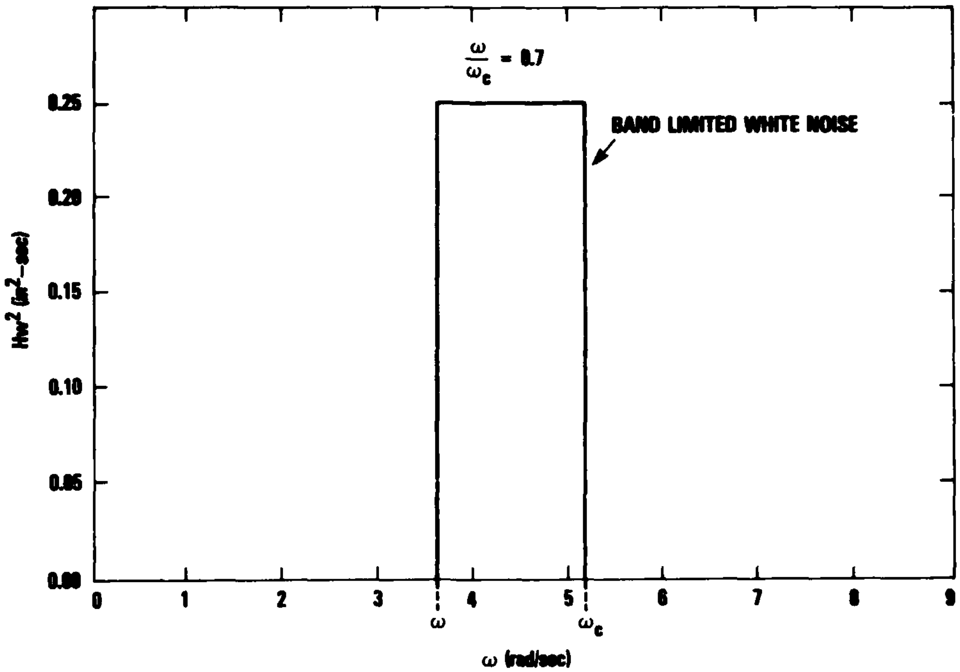

Figure 3 - Narrow-Band Variance Spectrum

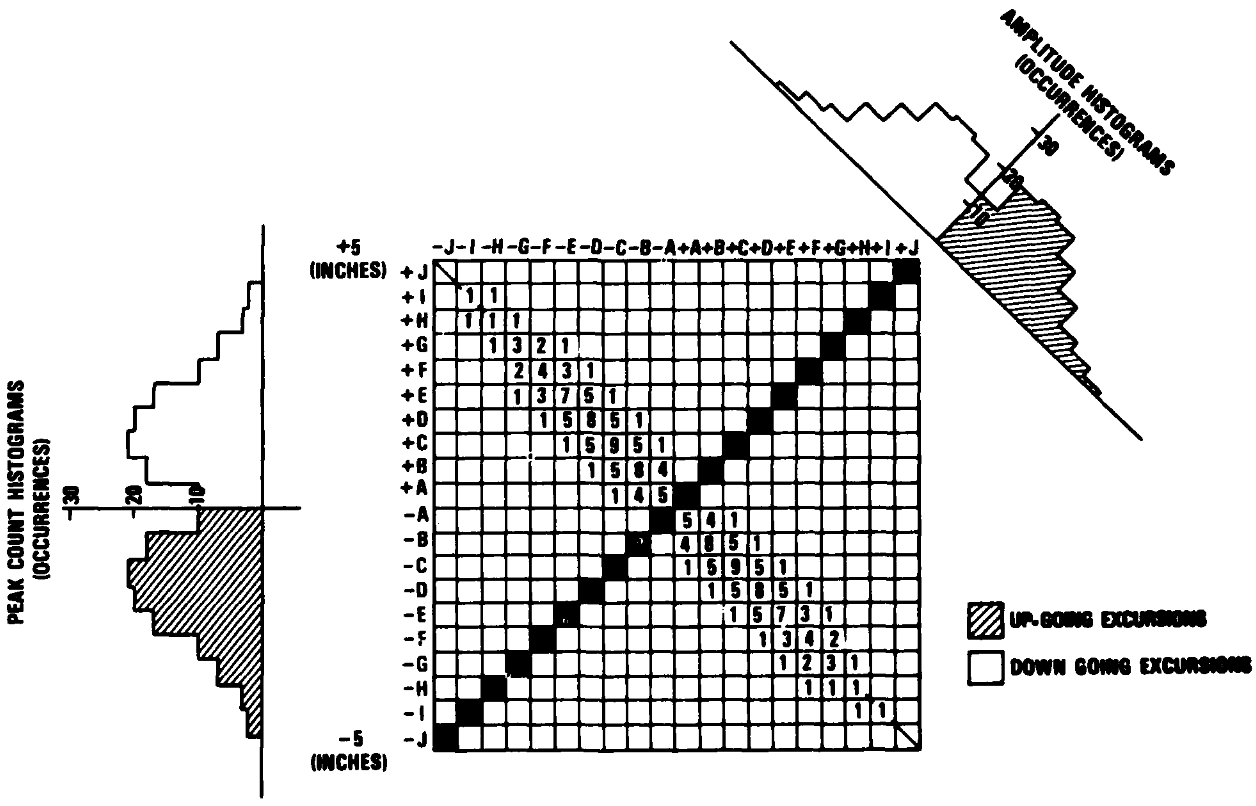

Figure 4 - HACYM Analysis of Narrow-Band Variance Spectrum ($\frac{\omega}{\omega_c}$ = 0.7)

histograms of peak counts and amplitude occurrences.* The characteristic of symmetry derives from the Gaussian nature of the process since data events having the same absolute values of mean and amplitude can be expected to have an equal probability of occurrence. The Rayleigh distribution of peak counts follows from Yang's mathematical formulation of the problem and since it is a narrow-band process, the histograms of peak counts and amplitude occurrences both have a Rayleigh distribution. For a stochastic process which is not "narrow-band," the pattern of half-cycle counts will spread in the direction of the null diagonal and become more nearly circular. As found by Cartwright and Longuet-Higgins,[5] the histograms of peak counts will approach a normal distribution as the width of the energy spectrum for a Gaussian process becomes increasingly large, i.e., as the process becomes more broadband. Thus, in general, one may expect that if wave height as a stochastic variable is Gaussian in nature the distribution of half-cycle counts in HACYM format will be symmetrical about the diagonals of the data matrix whether the process is substantially narrow-band or not. To the extent that the process is not narrow-band the HACYM dispersion pattern will necessarily increase in width.

These generalizations apply to random seaways both in nature and to recreations of them in towing tanks. Figure 5 presents the results of a half-cycle analysis of 114 wave height events associated with mechanically generated tank waves whose variance spectrum is represented by that of Figure 6. It will be seen that compared to Figure 4, which contains 108 wave events, the process of Figure 5 is more broadband (as can also be seen by comparing the spectra of Figures 3 and 6). The dispersion pattern of half-cycle counts is somewhat asymmetric because the larger waves in the tank are elevated slightly, i.e., they have trough-to-crest and crest-to-trough excursions which have small positive means. The amplitude and peak count histograms have distribution shapes which are roughly Rayleigh in character. Bearing in mind the relatively small sample size, the tank wave heights are considered here to be a working approximation of a Gaussian process which is only approximately narrow-band.

2.2 Non-Gaussian events** in Hurricane Camille Wave Data

HACYM analyses of time-series wave height data from Hurricane Camille have been performed.[2] Additionally, for the same half-hour data intervals, the variance spectra have been determined. Before discussing these as they relate to the distinctive types of waves identified by HACYM analysis, it is important that the storm be characterized as it developed at the deep water platform (in 340 ft of water) where data were obtained during the approaching storm. Since mechanical failure of the second of two Baylor type wave staffs occurred at 1617 hours (which was prior to the arrival of the eye of the hurricane) wave data were obtained only during the approach of the storm. (The first wave staff was rendered inoperable following passage of an episodic wave at [illegible] hours.) The wind during the data gathering period was almost constantly from [illegible] northeast direction which reflects the fact that the center of the storm pass[illegible] lightly to the west of the platform as it moved in a south to north direct[illegible]

*As explanined in App[illegible]dix A of Reference 2, the summations of half-cycle counts in rows and diagonals of the HACYM provide the wave height statistics analyzed by Cartwright and Longuet-Higgins[5] as crest heights and crest-to-trough heights, respectively.

**Events which would not have occurred if the wave height time-series were Gaussian.

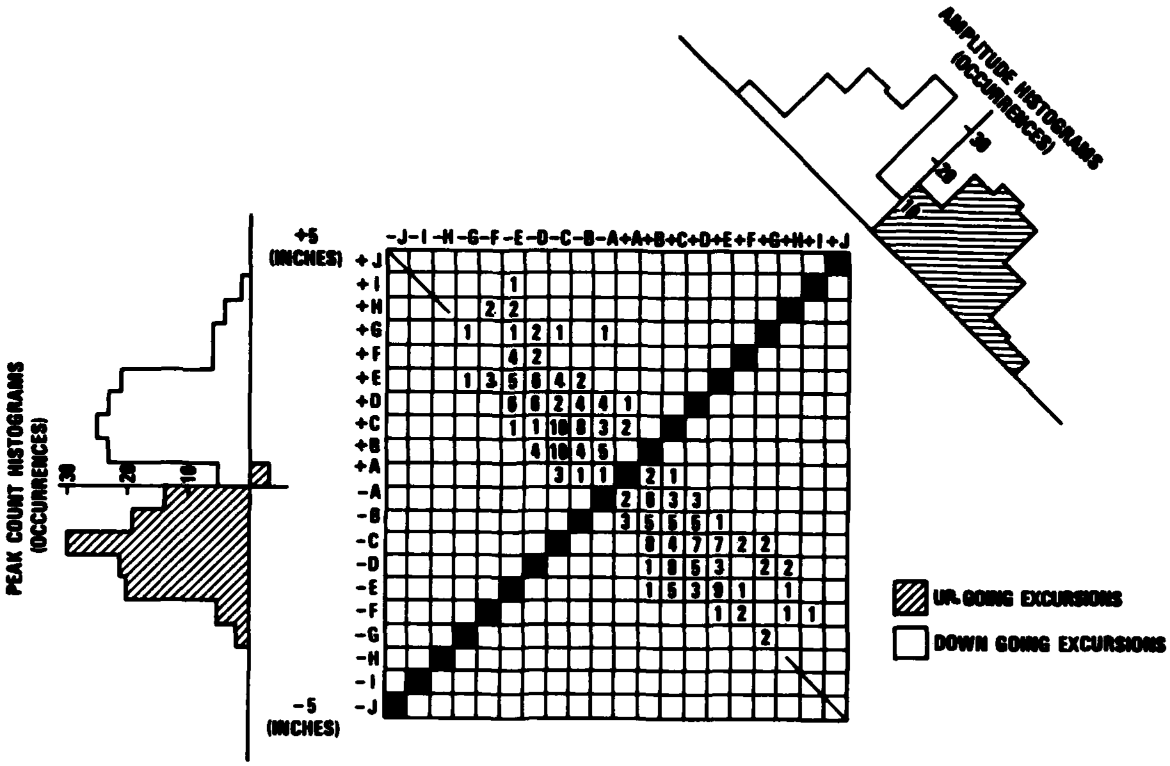

Figure 5 - HACYM Analysis of Test Tank Random Wave Data

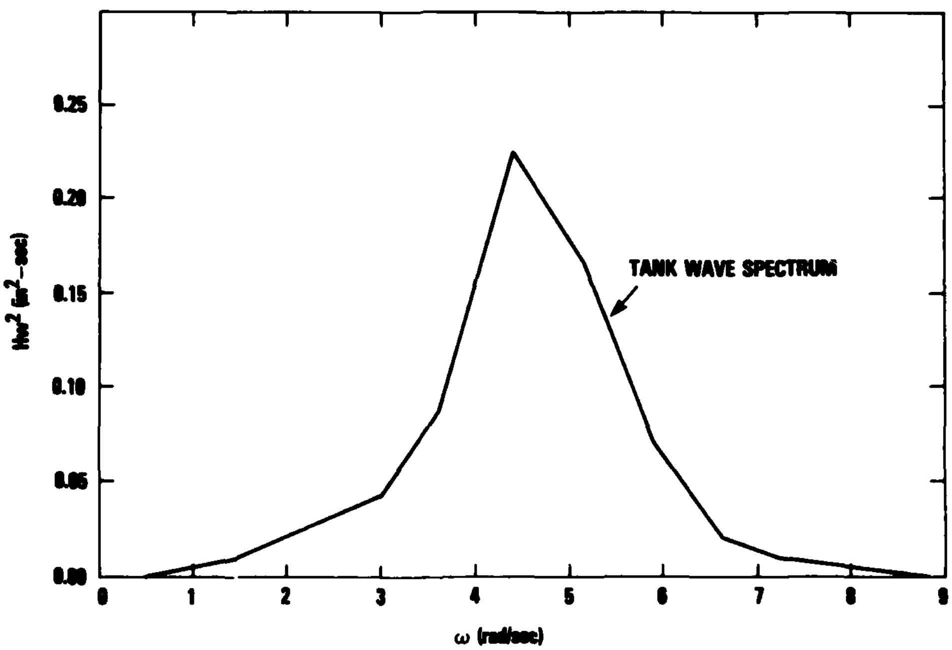

Figure 6 - Example Wave Height Variance Spectrum for Pneumatically Generated Tank Waves

The modal period* of the variance spectra associated with the waves was nearly constant at about 13 to 14 seconds from 1000 to 1600 hours.[2] This permits the following broad characterization of the seaway. Early in the storm the local wind velocity was less than would account for the observed modal period, even if the sea were fully developed[7]; see Figures 7(a) and 7(b). This is due to the fact that the local waves contained swell emanating from the approaching storm. Later the situation is reversed and the modal period was less than would be estimated for a fully developed sea corresponding to the observed average wind speed. Thus the waves were initially influenced by swell from the approaching storm, while later they were influenced substantially by locally strong and gusty winds.

A half-cycle analysis of Camille wave data beginning at 1000 hours finds wave events which appear to be Gaussian in nature.** Near 1200 hours, two episodic*** waves appeared in the seaway, the first of which (at 1155 hrs) had a ratio of wave height to significant wave height of about 2.4 to 1; see Figure 8(a). The event, shown in Figure 9(a), was composed of a group of three large waves, the center one of which was clearly the highest. The wave at 1222 hours was episodic primarily because it was elevated with respect to mean water level, the trough-to-crest height itself being by no means episodic; see Figures 8(b) and 9(b). As noted in Figure 7(b), these waves occurred at a time when the average wind velocity corresponded to that for a fully developed sea of the observed modal period.**** Thus the episodic waves occurred at a time when the seaway was, in terms of its modal period, "fully developed."

Beginning at 1430 hours, the half-cycle analyses of Figure 10 find that the seaway assumed a distinctly non-Gaussian character due to the continuing occurrence of large, elevated waves. Figure 7(b) shows that the average wind velocity had increased rapidly to approximately 50 knots by this time. The figure also shows an evident correlation between significant wave height and average wind speed where each is the average for a one-half hour interval. (This correlation would have been obscured if the interval of increased wind speed, particularly between 1300 and 1330 hours, had not corresponded closely to the chosen data analysis interval.) The time-series for three of the larger elevated waves are shown in Figure 11 from which it can be seen that these waves tend to stand alone in the time-series and to have waves of very small proportions running before them. In addition the period of the approaching elevated wave is substantially less than modal period. The wave of Figure 11(c) for example had an observed period of approximately (9/14) x 100 = 65% of modal period. If one may assume that wave length is proportional to wave period squared, then the wave length of this highest wave in the half-hour data analysis interval is less than one-half of that of waves corresponding to modal period (which

---

*Period corresponding to the peak of the spectrum.

**The wave events appear Gaussian in the sense of having a nearly symmetrical distribution in HACYM format.

***That is, data events which stand apart from all others occurring during the data analysis interval.

****In Figure 7(b) no allowance has been made for possible misalignment of wind and waves, nor has a correction been made for relating the measured wind velocity to a standard height.

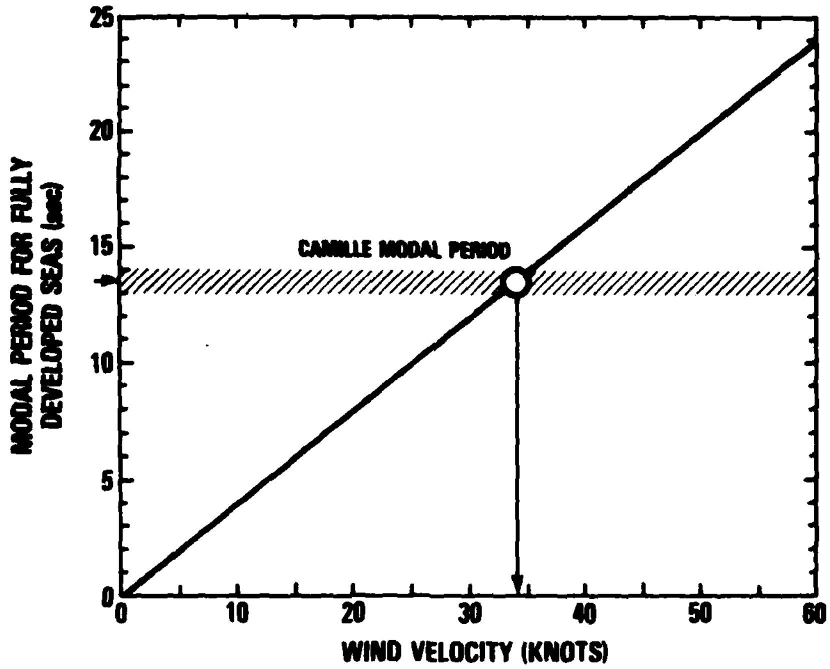

Figure 7a - Modal Period vs Average Wind Velocity for Fully Arisen Seas (from Table 2.1 of Reference 6)

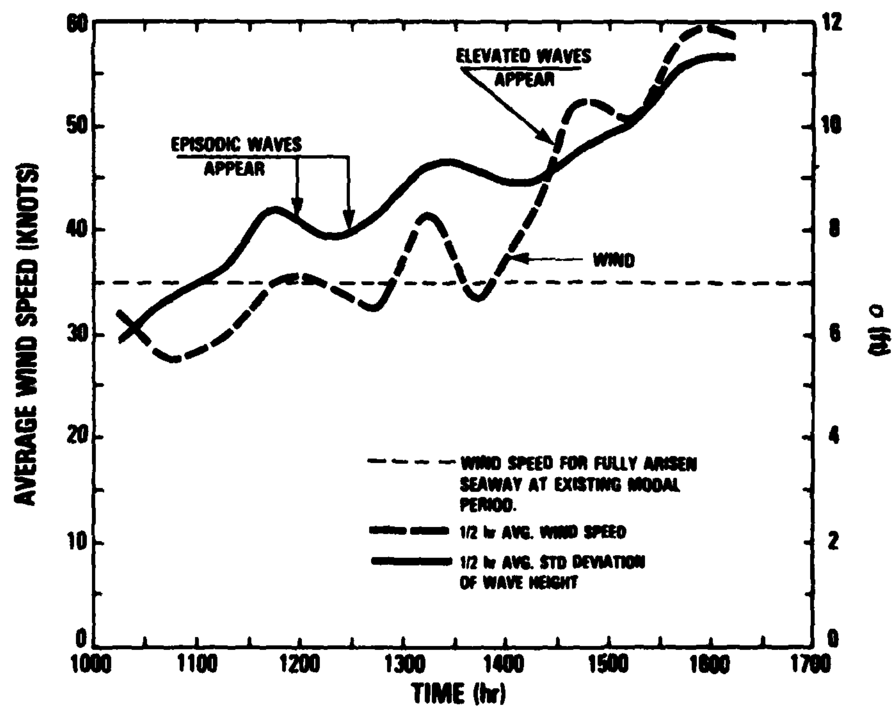

Figure 7b - Comparison of Average Wind Speed and Standard Deviation of Wave Height During Hurricane Camille

Figure 7 - Wind and Wave Correlations During Hurricane Camille

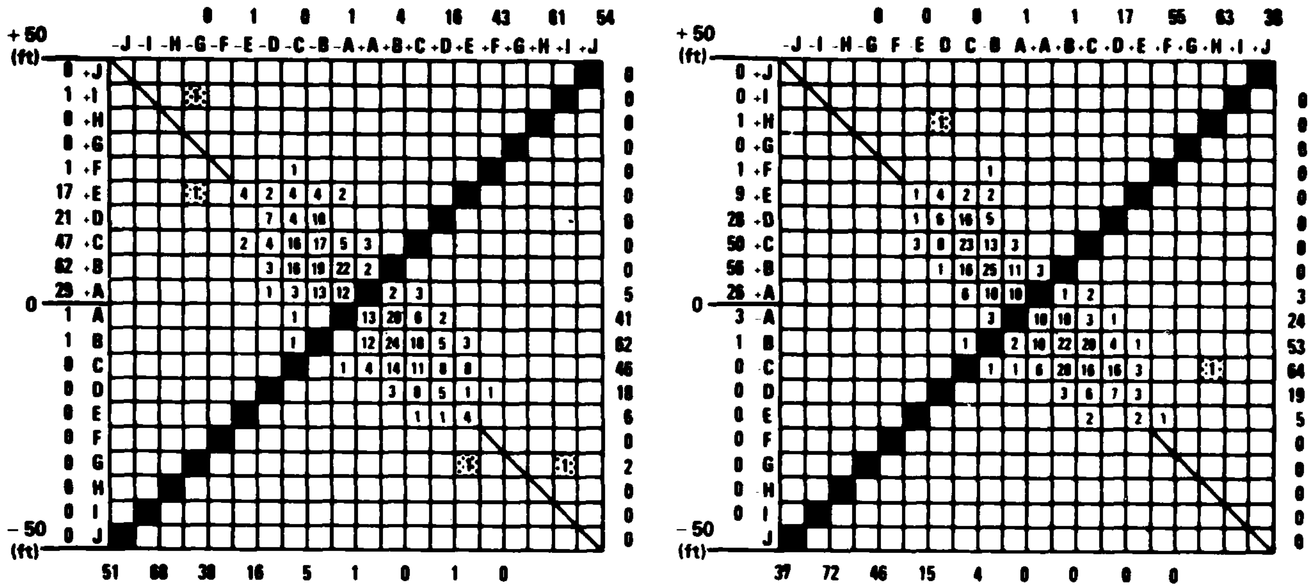

Figure 8a - 1130-1200 Hours

Figure 8b - 1200-1230 Hours

Figure 8 - Identification of Episodic Waves During Hurricane Camille

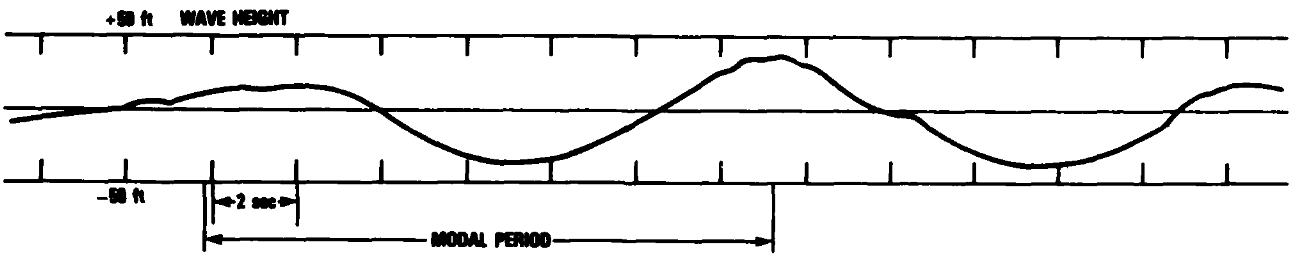

Figure 9a - Episodic Wave: 1155 Hours

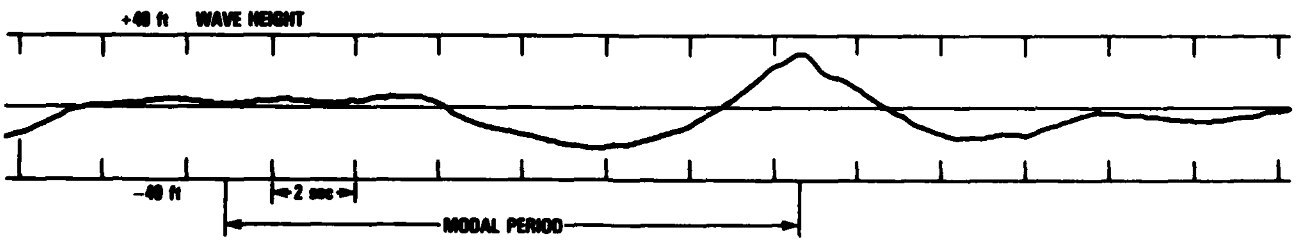

Figure 9b - Episodic Wave: 1222 Hours

Figure 9 - Episodic Waves Recorded During Hurricane Camille

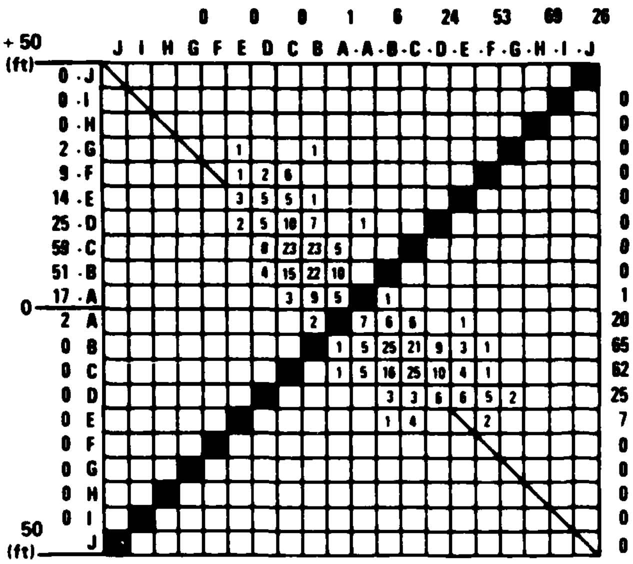

Figure 10a - 1400-1430 Hours

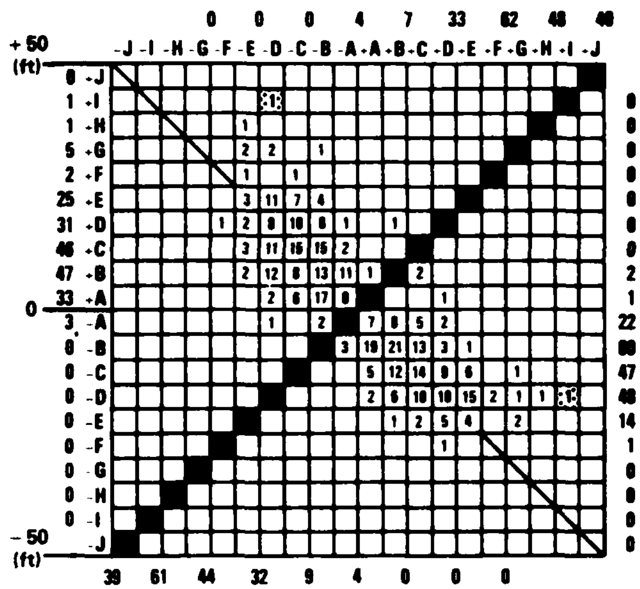

Figure 10b - 1430-1500 Hours

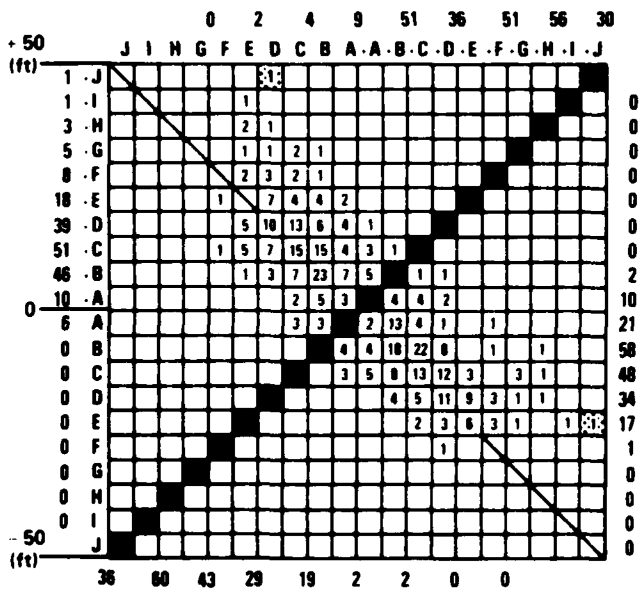

Figure 10c - 1500-1530 Hours

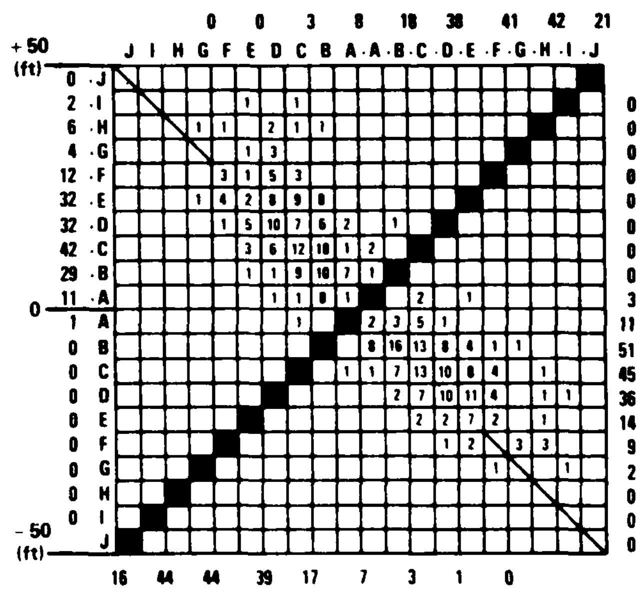

Figure 10d - 1530-1600 Hours

Figure 10 - Identification of Reoccurring Elevated Waves During Hurricane Camille

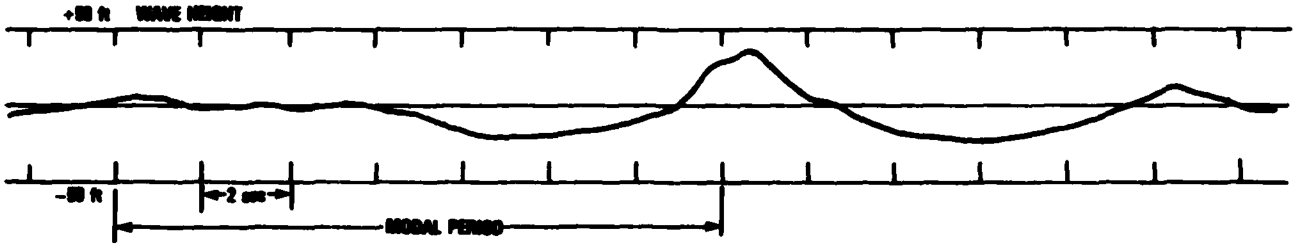

Figure 11a - Steep, Elevated Wave: 1457 Hours

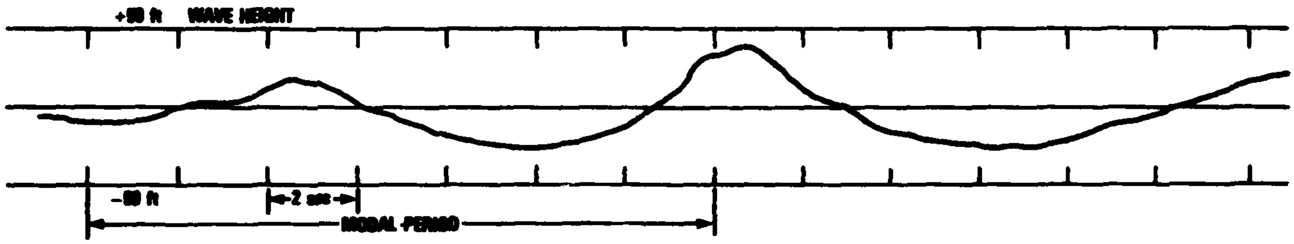

Figure 11b - Steep Elevated Wave: 1513 Hours

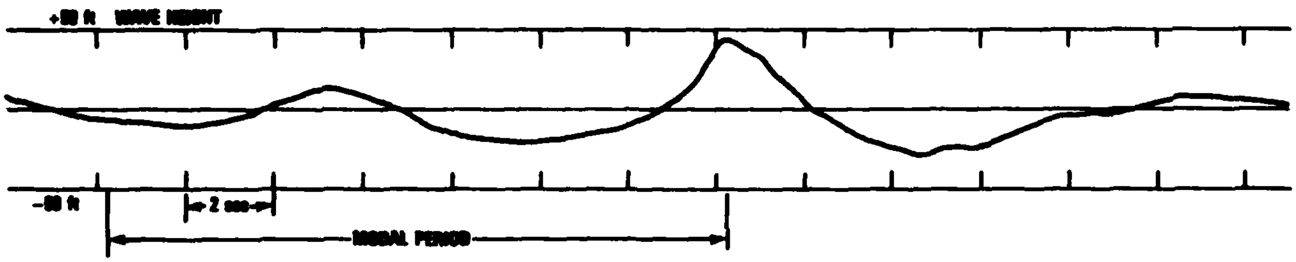

Figure 11c - Steep, Elevated Wave: 1522 Hours

Figure 11 - Steep, Elevated Waves Recorded During Hurricane Camile

are clearly the waves of dominant, time-average energy). The elevated waves of Figures 11(a) and (b) similarly have periods which are substantially less than modal period.

Wave steepness is not given directly by the time-series data of Figure 11, but an approximation can be obtained by assuming that the lengths of the waves in Figure 11(b) and (c) are approximately equal to 5.12 T^2 (ft). The average time interval between the crests of the preceeding and largest waves is approximately 9.5 sec while the average height of these large waves is 66 ft, which results in an estimated height-to-length ratio of $H/L \approx 66/(5.12 \times 9.5^2) = 1/7$. From this estimate, it is concluded that the waves of Figure 11 are both steep and elevated, and that the crest of the largest wave is close to, if not actually, breaking. Because of the asymmetry of these large waves as seen in HACYM format they are believed to also be properly characterized as "non-Gaussian" for reasons discussed above.

Whether or not the episodic waves of Figure 8 can be considered non-Gaussian cannot be easily determined. If the associated wave-height time-series were indeed Gaussian, particularly with respect to its extreme values, then the occurrence of an outlying wave event is possible although improbable. Regarding the improbability, Longuet-Higgins[8] observed that "The general conclusion then appears that changes in the strength of the wind or other generating forces are more important in producing variability in the wave amplitude than is the statistical variation of the waves at any one time." From a sampling point of view, however, the episodic wave event remains a possible although improbable event. (From a wave research point of view, the study of episodic wave events logically requires a prior examination of the effects of energy dissipation due to wave breaking since this mechanism is likely to impose a natural limit on wave height under ordinary circumstances. With the results of such research in hand, the subject of episodic wave events could then be approached on a more meaningful basis.)

2.3 Extreme Waves in Winter Storms

To date no wave data from a severe winter storm have been analyzed in HACYM format which are in any way comparable to that from Hurricane Camille. However, a review of several documented investigations of heavy weather damage involving U.S. Navy ships has established that waves having a time-series character similar to those of Figure 9(a) and Figures 11(a), (b), and (c) have been observed during winter storms and that they have resulted in severe structural loadings.[1] One episodic wave measured during a winter storm off the Irish coast was also noted in reference (1) to have a time-series character similar to that of Figure 9(a) although the overall proportions of the wave were smaller. These findings suggest that the non-Gaussian and episodic waves of Camille may have counterparts in severe winter storms.

The investigation of NOAA data buoy capsizing by Hamilton,[9] revealed a high degree of correlation between the capsizing of large, discus-shaped buoys moored off the U.S. East and West Coasts and certain sectors of severe winter storms. His findings suggested the potential value in the present study of correlating certain ship damage incidents with prevailing synoptic weather conditions.

2.4 Study Approach

The foregoing investigations influenced the conduct of this study in the following respects:

(a) The waves of Figures 9 and 11, which could have counterparts in severe winter storms, were believed to be sufficiently distinctive that ships officer's who have stood bridge watches during winter storms might have recollections of encountering them. Interviews with ship's officers of considerable at-sea experience were therefore sought to determine if this were the case.

(b) When reviewing ship heavy weather casualty cases of special interest, attention would be given to the time-correlated synoptic weather information associated with a ship's location within the storm in question. For this purpose surface weather maps and satellite cloud photos were obtained from the National Climatic Center, Asheville, N.C., and the National Climatic Center, Satellite Services, Division, Washington, D.C., respectively (after Hamilton[10]). Particular attention was also given to local wind data in regard to the apparent or measured rate of increase or decrease of wind velocity and any associated changes in wind direction. All information regarding the visual appearance of damaging waves was, of course, carefully reviewed for possible correlation with the waves of Figures 9 and 11.

3.0 LITERATURE SURVEY AND ANALYSIS OF SELECTED CASUALTY INFORMATION

While the open literature contains many descriptions of, or references to, ship heavy weather damage incidents, the number of these which deal with extreme wave encounters is quite limited with exception of those which have occurred in the Agulhas Current off the southeast coast of Africa. As a result of the work of Mallory,[10] a comprehensive summary of recent casualties resulting from episodic wave encounters is available for that ocean area together with an analysis of the synoptic weather conditions with which they are associated, Schumann[11,12,13] has further considered the tendency of wave energy to amplify when moving against a strong current in order to help explain the occasional presence of episodic waves in the Agulhas Current.

As a result of these prior investigations, it was felt that sufficient information is available to satisfy the objectives of the present study as they relate to that unique ocean area. This study thus addresses itself primarily to extreme waves in the open ocean about which much less is known at the present time.

3.1 Review of Prior Damage Surveys

Ship structural damage due to all causes, including heavy weather, was previously studied by Hawkins, et al.[14] In regard to heavy weather damage they found bottom damage due to slamming was the most prevalent type of damage but that:

"Precise details as to the circumstances under which the casualties occurred are lacking. Other than the fact that the majority of the cases occurred during winter months on various trade routes, little additional data could be found. Ship speeds, loading conditions, and other environmental details at the time of the casualties were, in most instances, either unreported or stated in very qualitative terms such as 'mountainous sea'."

With respect to other common sources of damage they found that:

"The next most prevalent form of heavy weather casualty uncovered during the survey was damage to structural components on the weather deck. Out of 23 cases 17 occurred in the area of the forecastle and the remainder at locations farther aft. Most involved damage to bulwarks and some to decks and internal structural members as well."

In discussing heavy weather damage trends in general they concluded that:

"Although these trends are significant, they have not yet been sufficiently validated to recommend and justify specific structural modifications. It is believed, however, that a more thorough examination of the casualties which produced these trends would be of value. Particularly in cases of slamming damage, and to a lesser extent cases involving damage to the forecastle and weather deck, it would be possible to attain a better understanding by further examination of the environmental conditions and of the hull form and above water configuration in the bow area of each ship involved."

While no attempt has been made in this study to consider hull form and above water configuration aspects of heavy weather damage generally, these variables are reviewed and discussed briefly in connection with certain heavy weather damage cases. The lack of detailed operating and seaway information noted in connection with bottom slamming damage cases has been overcome here to some degree by placing emphasis on a review of information contained in U.S. Coast Guard casualty investigation reports which furnish more specific information than is generally available from the open literature.

A broad study of weather related ship casualties over a 10-year period was conducted by Quayle,[15] who found that there is a substantial increase in casualties during winter months and that the majority occur in coastal and near coastal areas.* His comprehensive survey also implied that general surveys typically result in general conclusions. From the point of view of furnishing information of particular value in the design of ships to withstand heavy weather operation, general surveys tend to be of limited value since the most important information is usually associated with the details of individual casualties. The present study has accordingly sought damage cases where more than the usual information regarding the circumstances of the casualty is available.

3.2 An Interpretive Summary of U.S. Coast Guard Heavy Weather Damage Information

The U.S. Coast Guard Office of Merchant Marine Safety, Marine Investigations Division furnished a computer listing of their Reports of Vessel Casualty or Accident (Form CG-2692) under the subject classification "U.S. Inspected Vessels of over 1000 G tons Involved in Casualties Relating to Heavy Weather: Fiscal 1970-79." The listing contained 1150 entries, the majority of which, based upon a sampling approach, did not involve damage due to extreme waves.** In order to identify those

*The study included grounding and collision cases.

**The term "extreme wave" is employed here in the context of a wave of damaging proportions, but of undefined character regarding height, period, steepness, etc.

cases most likely to be of interest, the coded listing was searched for those cases satisfying the criteria: damage in excess of $50,000 in seas of height greater than 15 ft. All groundings and collisions meeting the criteria were arbitrarily disregarded. The cost criterion was later modified and all cases involving seas or swells in excess of 40 feet were included regardless of the cost of damage repair.

A tabulated summary of 38 cases identified in this manner is presented in the Appendix. Most of the information relevant to this study which was available in the CG-2692 forms has been included in Table A-1 of the Appendix. Based upon these data, Table 1 on page 17 has been prepared to call attention to certain trends which are believed to be of particular importance. The first of these is the relative dominance of local wave loadings, compared to over-all hull girder loadings, as a source of heavy weather damage. Of the 38 cases summarized here, 26 involved damage due to local wave loadings compared to 4 cases where cracking in the primary hull girder was reported. In the most serious of the latter (Case No. 15), a 16-foot long crack developed. In this instance, the ship's master was cited for operating his ship at 16.5 knots in 20-to 50-foot seas.

A similar trend toward local wave impact damage, as compared to hull girder loading damage, was also noted by Buckley[1] as a result of a survey of heavy weather damage experienced over a 10-year period by U.S. Navy ships.

Table 1 also shows an evident trend toward container damage (mainly containers on deck) since 12 of the 38 cases involved such damage. Of these, 5 were specifically attributed to the occurrence of extreme roll angles in the seaway. One case (No. 1) involved tie-down failures which were apparently the result of hull girder torsional deflections in the seaway.

No attempt was made in preparing Table 1 to determine the statistics of extreme wave encounters since the results could be misleading. The reason for this decision was that the information required by the CG-2692 form does not specifically address the subject of extreme wave encounters, although in some cases reference is made to "a series of mountainous waves," "vessel suddenly rolled 40 degrees to port", "we were suddenly lifted by a huge swell", etc. The problem at hand is illustrated by Case 28 of Table A-1 for which additional information happens to be available. In this instance the SL-7 class container ship S.S. SEA-LAND GALLOWAY experienced damage in a relatively moderate seaway of 8-12-ft seas, 13-20-ft swells, with local winds of 30 to 40 knots. Discussion of SL-7 class heavy weather damage experience with a naval architect familiar with the ship revealed that it had been proceeding at approximately 30 knots when it encountered an unusually large wave in the seaway which could be seen approaching from a distance, but which could not be avoided nor the ship slowed substantially before it was encountered. The resulting bending moment on the forward portion of the hull girder was sufficiently large as to cause paint to flake off locally due to plastic tensile strains on one side of the hull while on the opposite side local "crinkling" of the plating occurred. In addition to this information, an unpublished list of extreme scratch gage readings by ship and date furnished by Teledyne Engineering Services revealed that the incident in question produced the 4th highest hull girder scratch gage strain reading recorded on this class of ship out of a total of 36,011 individual readings. These findings illustrate the extreme nature of the wave encountered in comparison to the other waves in the seaway as well as the fact that no attempt was made to identify it in the CG-2692 form.

TABLE 1 - TRENDS NOTED IN SURVEY OF U.S. COAST GUARD HEAVY WEATHER DAMAGE INFORMATION

Reference Number of Table A-1	Damage Due To Local Wave Loads	Hull Girder Damage*	Container Damage	Remarks
1			X	Racking of hull girder believed to have precipitated loss of 47 containers
2				Rudder failure
3			X	
4	X			Bulwark carried away
5	X			$400,000 cargo loss due to sea water entry
6	X		X	Main deck holed in three places
7	X			
8			X	Vans went over the side following 38° roll
9			X	6 vans lost overboard following 40° roll. 22 others damaged.
10	X			Sea water entry into wing ballast tank
11	X			Port hole window failure. Damage due to sea water entry.
12				Mooring anchor failure-drilling barge
13			X	Deck cargo lost overboard following 53° roll
14	X		X	Containers lost; foredeck setdown
15		X		16' long hull girder crack. Ship driven at excessive speed in seaway
16	X		X	Container broke loose following 35° roll
17	X			Emergency generator room flooded

*Damage related to overall hull girder bending, shear, or torsional loadings as evidenced by local fractures in primary hull girder structure.

TABLE 1 - TRENDS NOTED IN SURVEY OF U.S. COAST GUARD HEAVY WEATHER DAMAGE INFORMATION (CONTINUED)

Reference Number of Table A-1	Damage Due To Local Wave Loads	Hull Girder Damage*	Container Damage	Remarks
18			X	Container lost overboard, attributed to vessel motions
19	X			Bow thruster room flooded
20	X		X	Beam swell damaged four containers
21	X			Wing bridge damage attributed to "freak" wave
22	X			Wing bridge damage; sea water entry damage
23	X			Water entry damage due to main deck hatch failure
24	X		X	Containers damaged by wave impact
25	X			Salt water damage to "transporter" motors in following seas
26	X			Green seas shipped due to extreme roll in following seas
27	X			Foredeck and appurtenance damage
28		X		Hull plating and hatch corner damage
29	X			Pilot house and other window failures. Bulwark and breakwater damage
30	X			Foredeck dished-in. Wing bridge and window damage
31		X		14" crack in main deck. Port side bulwark damage
32	X			Foredeck set down; Window failure and cabin flooding

*Damage related to over-all hull girder bending, shear, or torsional loadings as evidenced by local fractures in primary hull girder structure.

TABLE 1 - TRENDS NOTED IN SURVEY OF U.S. COAST GUARD HEAVY WEATHER DAMAGE INFORMATION (CONTINUED)

Reference Number of Table A-1	Damage Due To Local Wave Loads	Hull Girder Damage*	Container Damage	Remarks
33	X	X		Damage to forecastle deck plating, breakwater, and windows. Cracking at No. 1 hatch
34	X		X	Bow thruster room flooded, containers stove in
35	X			Extensive wing bridge damage. Deckhouse plating torn, Masters quarters flooded
36	X			Appurtenance damage
37	X			Damage survey apparently incomplete
38	X			Bow plating and framing damage

*Damage related to over-all hull girder bending, shear, or torsional loadings as evidenced by local fractures in primary hull girder structure.

No supplementary information for Case 29 of Table A-1 is available, but it will be noted that the S.S. SEA-LAND McLEAN operating in an entirely different ocean area experienced significant foredeck and deckhouse damage in 15-20-ft seas, 10-12-ft swell, and winds of 45-50 knots. In this case the ship, while proceeding at reduced speed (15 knots), experienced damage under sea conditions which should not normally have caused such damage. As with Case 28 this raises the question of whether one or more unusually large waves were encountered. The description of casualty information contained in Table A-1 suggests that this may have been the case, but since no explicit comment was made regarding the possibility obviously no substantive conclusion can be drawn.

From these two examples, it is believed evident that the information normally provided on the CG-2692 form does not provide an adequate basis for relating ship damage to extreme wave encounters.

3.3 Selected Casualty Information

One casualty case included in Table A-1 together with certain other extreme damage cases are reviewed in Section 5 of this report because of their importance in assessing the effects of extreme waves on ship structure. These cases are also important with respect to the classification of such waves and will be considered further in that context rather than as part of the general casualty survey.

4.0 PERSONAL CONTACT SURVEY

The personal contact survey was intended to obtain information regarding ship casualties which was not readily available in the open literature as well as to compare general damage trends of commercial ships to those noted previously during a heavy weather damage survey of U.S. Navy ships.* These objectives were not changed during the study. However, interviews with several shipmasters and ship's officers were added to the survey when it was decided that the time-series waves of Figures 9 and 11 might be used to help determine if such waves had been observed during winter storms.

4.1 Visit to American Bureau of Shipping (ABS)

The general tendency toward heavy weather damage as a result of local wave loadings (as opposed to over-all hull girder loadings) noted in U.S. Navy in-house research[1] was affirmed by the head of the ABS Hull Department. In cases where substantial damage is experienced by ABS-classed ships, the structure involved is generally checked for conformance to ABS rules and if found satisfactory is then returned to its original configuration. Despite the preponderance of local damage, hull girder failures were not unknown and reference was made to the S.S. FRUEBEL EUROPIA which experienced a major buckling failure during a westbound voyage to New York City, approximately 12 years ago.

With respect to operations off the Southeast coast of Africa, a trend toward postside bow damage has been noted. Structural failures in the area of bulbous bows, such as recently experienced by the S.S. ENERGY ENDURANCE, were believed due

*The damage survey of Appendix A had not been undertaken at this time.

in some cases to the discontinuance of longitudinal members in the immediate vicinity of the bulb.

A tendency in recent times toward fo'c'sle damage has been noted and the problem is currently under study. (The casualty data of Cases 27, 29, 30, 32, and 33 of Appendix A reflect such damage for one class of ship). On the other hand, the International Association of Classification Societies recently reduced deckhouse front scantlings with respect to supporting structure. Deckhouse window failures, such as noted in Case 32 of Appendix A (which was available for discussion at this time), are generally not a problem since steel deadlight covers are typically required by classification rules for lower level windows to preclude flooding in heavy weather. However, it was noted that bridge windows have tended to become larger over a period of years and their strength characteristics have been under study as a result of concern for wave impact loadings.

4.2 Visit to United States Salvage Association, Inc.

U.S. Salvage Association representatives also confirmed that local wave loadings are a primary source of heavy weather damage. Bottom slamming damage was relatively common for ships designed during the World War II era due to their particular overall lengths and lack of longitudinal framing. The increased lengths, tendency toward "V" hull forms forward, and longitudinal framing of more modern ships have considerably reduced the incidence of bottom slamming damage in recent times.

Foredeck damage as exemplified by Case 32 of Appendix A tends to be a function of the individual ship design. For example, six ships of this class which were recently surveyed by the U.S. Salvage Association had evidence of internal damage in the foredeck area. Other modern ships, with lower-speed hull forms and somewhat shorter lengths, have been found to be relatively free of foredeck damage by contrast. Deckhouse window damage has not been a significant problem due in part to the ABS requirement for deadlight covers for windows on forward facing structure at the main deck level. On the other hand gangway damage has been an item of reoccurring damage and is of some concern since gangways cost on the order of $25,000 each to replace. Lifeboat damage has been found to be reduced significantly since construction was changed from sheet metal to glass-reinforced plastic.

As far as catastrophic structural failures in heavy weather was concerned, instances of ship losses were known but no particulars were available.

4.3 Interview of Two Ship Masters

The ship masters were interviewed; their operational backgrounds are briefly as follows:

Captain "A" - Considerable operating experience in northern Europe, Mediterranean, and Far East areas. Commanded dry cargo ships worldwide; container ships in northern Europe and the Mediterranean area; liquified natural gas (LNG) ships in the North Atlantic and Mediterranean areas, also tankers operating between St. Croix and New York City.

Captain "B" - Considerable experience operating between northern Europe and the U.S. East Coast. Commanded breakbulk and dry cargo ships transiting between U.S. West Coast and South East Asia; container ships operating in the North Atlantic, Mediterranean, and U.S. East Coast areas; LNG ships operating between the Mediterranean and the U.S. East Coast; tankers operating between St. Croix and New York City.

Each has a total "at sea" work experience of about 35 years.

The interview began with a brief introduction to the study being conducted followed by a summary of the information gathered up to that time regarding the existence of the "non-Gaussian" waves of Figures 9 and 11. The ship masters were then asked if they had observed large storm waves which were similar in time-domain character.*

Steep, Elevated Waves: Neither master could recall seeing steep, elevated waves in a storm driven seaway although large steep waves were relatively common in severe storms. Among such waves the steep, just-breaking and especially the long-crested wave of this description is the one most likely to cause damage. The abstract of the deck log from the S.S. SEA-LAND McLEAN was reviewed in detail with them at this point (See Figure 12) and they indicated that the evident correlation between increasing wind velocity and the appearance of "very high steep swells" was typical; in fact the entire storm development and resulting ship response in this case was considered to be "right out of the mold." Captain "B" added that steady veering of the wind from southwest to northwest did not always occur. Instead it would occasionally go back to southwest and then return to northwest in winter storms.

Episodic Wave Groups: The outlying (or episodic) wave group was familiar to both officers, although they were encountered only occassionally in storms (perhaps 3 or 4 times if encountered at all). Generally, if such a wave group was encountered it was relatively certain that a storm having central winds on the order of 60 knots or more was in the vicinity. Their impression was that wind intensity had a good deal to do with the appearance of such waves. Since groups of large waves have also been seen after a storm has died down, it was presumed that the strong central storm winds were the cause of these large waves rather than the local, dying wind field. (Unfortunately, the interviewer was not aware at this time of the importance of determining whether such waves were aligned or misaligned with respect to the local seaway).

Both officers stated that the distinctive waves which had been discussed up to this point were generally less of a problem for them than large, swell-type waves which suddenly appeared from a direction substantially different from that of the local seaway. In a typical situation the ship's speed and heading would have been chosen so as to minimize rolling, slamming, and green water on deck in the storm. The arrival of the misaligned swells generally resulted in severe rolling of the ship, which in turn caused concern for cargo shifting and related problems.

As a miscellaneous question, the interviewer asked whether a fresh cross-wind acting on a swell type seaway could quickly dissipate the swell. They both agreed that it could. (This observation had been made previously by another party.)

*The comments which follow have been organized to apply to the relevant wave type. They were not necessarily made in the order implied here.

Figure 12 - Steep Long-Crested Wave as Seen from USS Independence (CV-62) During Winter Storm

Figure 13 - Steep Long-Crested Wave as Seen from Unidentified Ship
(Photo from Surveyor, May 1968, pg. 23)

1/16/74

00-04 0033 Texel L/V abeam 130°, 8.2.0' cast. Vessel pitching mod. to easily in a rough to mod. SW'ly sea and mod. avg. swell. Weather moderating after 0230. Shipping seas over fore dk and hatches. Routine inspections.
Bar. 30.08 Wind SWxW 5 (19-29 kn)

04-08 0800 Moderate to rough SSW'ly sea. Vessel taking light seas over bow and main deck. Heavily o'cast. Routine inspections.
Bar. 29.84 Wind SSW 5-6 (19-31 kn)

08-12 0759 Greenwich buoy @ to port 5.7 mi. 0842 Owers L/V @ to st'bd 9.6 mi. 0927 St. Katherines Pt. @ to st'bd 11.7 mi. off c/c to 269° g&t 1021 Anvil Pt. @ to st'bd 11.8 mi. 1058 Bill of Portland @ to st'bd 6.9 mi. off 1100 engine room given 90 min. notice to slowdown. Partly cloudy with rain, passing squalls. Vessel pitching mod. in a rough SW'ly sea, taking heavy spray across decks. Routine inspections.
Bar. 29.46 Wind SW 7-8 (32-46 kn)

12-16 1222 r/s 60 rpm. Approaching Berry Head, maneuvering to let Pilot off vessel. 1255 Pilot Roggen away in launch p/s. 1308 increase to 80 rpm. 1323 increase to 90 rpm. 1327 gyro 200°. 1342 reduce to 80 rpm. to ease vessel in heavy seas and increasing wind. 1405 r/s 75 rpm. 1425 r/s 60 rpm. 1449 r/s 55 rpm. 1451* r/s 45 rpm. O'cast vessel rolling mod. and pitching deeply in a very high rough WSW sea and very high and steep swells. Shipping seas over decks and hatches. Routine inspections.
Bar. 29.42 Wind WSW 11 (64-73 kn)

16-20 1648 c/c 240° gyro. 1838 r/s to 30 rpm. 1851 r/s to 25 rpm. 1900 i/s to 30 rpm. on port engine. Heavy wind gusts short, deep and heavy swells. Vessel pitching deeply at times, taking seas over bows, hatches, and main deck. Routine inspections.
Bar. 29.75 Wind WxN 11 (64-73 kn)

20-24 Vessel hove to in storm conditions, mountainous seas. Master conning. Partly cloudy good vis. Vessel proceeding on 30 rpm. port engine, 25 rpm. stbd engine to maintain steerage way. Pitching and rolling heavily at times in a very rough NNW'ly sea. Taking heavy spray across weather decks.
Bar. 30.21 Wind 8-9 (39-54 kn)

*Entries this date Jan. 16, 1974

1450 Vessel encountered mountainous swell, shipped heavy seas over foc'sle head from a direction of approx. 15° on the port bow. Tension winch control stations torn off foc'sle head, other damage to be ascertained when access to foc'sle head is possible. In ships office, port bent out, office flooded. Rooms #31, #32 on 01 level, windows broken, rooms flooded. Room #33 window bent at hinges, some salt water damage. Room #13 at 02 level two windows bent at hinges some salt water damage. Rms. #31, #32, Section of overhead, paneling approx. 5'x5' broken off in each room. 1500-1630 Lower mooring station fwd pumped dry with ships educter, water entered through holes in foc'sle head where bases on tension winch controls had been anchored. 1630 Open windows Rms. #31, #32 and ships office temporarily plugged with mattresses etc. to prevent further entry of sea water.

Figure 14 - Abstract of Deck Log from S.S. SEA-LAND MARKET in Southwest Wind Field of Winter Storm

4.4 Interview of United States Coast Guard Officers

Three U.S. Coast Guard Officers were interviewed. Captain "A" and Cdr. "B" had previously served on ocean weather ships manned by the U.S. Coast Guard, and Admiral "C" (part-time attendance) had considerable at-sea experience including service in the U.S. Merchant Marine. A brief introduction to the study was given followed by a description of the large "non-Gaussian" waves identified in Hurricane Camille and a summary of several ship damage incidents in which such waves had apparently been encountered.

Steep, Elevated Waves: As in the interview with the ship masters, the elevation of steep waves was not a characteristic that was clearly recalled. Captain "A" stated that in a storm in which waves approximately 20-feet high or more were encountered every 7th or 9th wave was typically steep and potentially dangerous. When the interviewer stated that such a trend was not evident in the Camille wave data, Captain "A" further characterized these waves as having a "hole-in-the-sea" in front of them. This was recognized by the Interviewer as describing the time-series of wave height preceding the steep, elevated waves of Figure 11. Regarding the time rate of occurrence of such waves, a rate of roughly one every 10 or 15 minutes was considered representative, which is consistent with the occurrence rate after 1500 hours during Hurricane Camille when this type of wave began to appear.* The wave was further characterized as being aligned with the local seaway and distinctly long-crested. Such waves were considered dangerous because they could result in green water on deck and could damage lifeboats, gangways, and other appendages.

Episodic Wave Groups: Outlying groups of three waves (typically) were familiar to each of the officers. Such waves intruded into the local seaway at angles up to 30° from the dominant wave direction. They were described as being "not that steep" and of having a speed of propagation noticeably greater than the other large waves in the seaway. Where these waves intersected with the large aligned waves, a prominant short crested (1000-1500 yards in length) wave conformation occurred which could be seen clearly "walking at you." This distinctive formation had been given the colloquial name "The Three Sisters." It was sufficiently prominent that it had been tracked occasionally on the ship's radar as it approached. Admiral "C" added that "The Three Sisters" had also been seen in Lake Superior. When the wave group arrived, it usually resulted in extreme roll angles. Injuries had occurred on occasion due to the large and unexpected roll motion. Wave groups of this type were most often encountered in a seaway having wave heights on the order of 25 to 30 feet. or more.

With regard to the ability of a crosswind to "knock down" a swell, Cdr "B" stated that this was well known in navy tender operations and that operations previously cancelled because of a large swell were frequently rescheduled in the near term when a crosswind arose because the decay of the swell was both predictable and rapid.

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*At this point it became apparent that the "seven [illegible] wave" characterization applied to only the largest waves in the seaway [illegible]. It was later realized that the elevation of the wave was not immediately evident because the trough of the wave was not always visible (see Figure 13), nor was it of immediate concern.

Several months after this interview, Captain "A" and Cdr "B" were revisited to determine if the waves of Figures 13 and 14 were representative of the steep, "every 7th" type of wave they had previously described. Both officers stated that the photos were indeed representative of the waves which they had previously characterized as being large, steep, long-crested and aligned with the local seaway.

5.0 ENCOUNTERS WITH LARGE, NON-GAUSSIAN WAVES

The following case studies are intended to (a) provide further insight into the unique characteristics of large, non-Gaussian type waves and to (b) help illustrate their significance in ship structural design. The individual cases have been grouped according to the wave type believed to be involved in the casualty, i.e. steep, elevated, or episodic. The latter type of wave has been further classified according to whether the damaging wave was believed to be aligned or misaligned with the local seaway. The former will be referred to here as "large grouped waves" and the latter as "episodic wave packets". This choice of terminology is discussed in Section 6, where consideration is given to the origin of episodic waves.

5.1 Casualties in Steep, Elevated Waves

Steep, elevator waves appeared in Hurrican Camille when the wind speed built rapidly to a time average value of about 50 knots with gusts to 85-90 knots. They can be characterized as having a maximum height of about 1.6-1.7 times significant wave height* and a period of 70 percent or less of modal period for the corresponding wave height variance spectra. In the case of the steepest and most elevated waves, the preceding wave is characteristically small, while the wave itself is very steep on its forward face. Representative time-series from the Camille wave data are shown in Figure 11. As a result of interviews with the ship's officers who had served on ocean weather ships, these waves have been characterized as typically long-crested as seen in Figures 12 and 13.

(1) CHESTER A. POLING** CASUALTY

This small coastal tanker broke in two off Cape Ann, Massachusetts, during a rapidly developing winter storm in January of 1977.[16] The sequence of wind build-up associated with the casualty is as follows:

	WIND		
TIME	VELOCITY (knots)	DIRECTION	REFERENCE
0700	18, Gusts to 22	SE	16, pg. 11
0840	30 to 35	ENE	16, pg. 2
1030	steady 50	not given	16, pg. 11
1130	55 to 60	not given	16, pg. 11

Note: The National Transportation Safety Board's analysis on pg. 18 of the reference estimates winds from the east to southeast at 35 to 45 knots with gusts to 55 knots at 1035 hours when the casualty occurred.

*The average of the one-third highest waves.

**Length = 281 feet, beam = 40 feet, displacement = 5000 long tons.

Based upon the rapid buildup of wind velocity it is presumed that the local seaway was substantially "over-driven"* and apt to contain steep, elevated waves similar to those of Hurricane Camille, but of smaller height and period. For discussion purposes the wave of Figure 11(c) will be used as a model with its height and length proportions retained. From Figure 11(c) we find H = 66 ft. Assuming $L \approx 5.12 \times T^2 = 5.12 \times 9.0^2 = 415$ ft results in a ratio of H/L of 66/415 = $1/6.3 \approx 1/7$. As the seaway encountered by the CHESTER A. POLING grew, the storm waves were estimated by the crew to be 20-25 ft high with distances between crests of about 150 ft (see page 5 of reference 16). Using a ratio of H/L = 1/7, the observed wave heights would imply associated wave lengths of 20 to 25 x 7, or 140 to 175 ft for the larger waves which is in general agreement with the observed value of 150 ft.**

It has been found in reviewing other visual wind and wave estimates for rapidly building seaways that the observed wave heights in feet are generally reported to be about one half of the stated wind velocities in knots.*** At the time of this casualty, winds were reported to be about 55 to 60 knots with estimated heights (presumed here to be close to significant wave height) of 25 to 30 feet which is consistent with this rough "rule of thumb." During the phase of Hurricane Camille in which steep, elevated waves were encountered, maximum wave heights were equal to about 1.6 - 1.7 times significant wave height. This would suggest a maximum individual wave height in this case of about 25 to 30 x 1.65, or 41 to 49.5 feet, which is compatible with the estimated value of 45 feet for the wave reported by the wheelhouse lookout to have caused hull girder failure (see page 6 of reference 16).

The height-to-length ratio of 1/7 estimated above suggests a wave length of about 315 feet for a 45-foot-high wave which is of relatively critical proportions for a ship having a length of 281 feet. Given non-Gaussian waves of the steep, elevated variety in this seaway, a relatively small, high block coefficient, ship such as the CHESTER A. POLING could have experienced wave-induced hull girder bending stresses of an extreme nature as implied by the following: "About 1035, the POLING encountered an unusually large wave, estimated by the seaman of wheelhouse lookout to be about 45-ft high. As the bow rose on the wave, another bang was heard and the vessel lurched. The hull split about 27 ft forward of amidships."[16]

(2) SEA-LAND MARKET**** DAMAGE INCIDENT

The deck-log abstract of Figure 14 identifies another critical aspect of the steep, elevated waves associated with a large, rapidly building seaway. The CHESTER

*See discussion of Section 6.1.1.

**This height to length ratio applies primarily to the large non-Gaussian waves in the seaway. The majority of the large (Gaussian) waves would be expected to have a height to length ratio closer to 1/14 in order to account for the observed modal period as in the case of Hurricane Camille wave data.

***Use of this "rule of thumb" is intended here as a test of credibility for the reported wave heights and not as a basis for estimating wave heights. It is intended to apply only to rapidly building seaways.

****Length = 946 feet, beam = 106 feet, displacement = 47,700 long tons.

A. POLING casualty helps to illustrate that high block coefficient ships having lengths in the range of 250 to 450 feet (i.e. winter storm to hurricane wave proportions) should be studied carefully with respect to maximum hull girder shear and bending loads. The SEA-LAND MARKET on the other hand calls attention to a problem of a different type in a seaway containing steep, elevated waves. In this case we are dealing with a long ship (946 feet) having a very fine entry forward which has experienced damage in the foredeck and deckhouse area due to "deck wetness" (see the Appendix). The ship length is substantially greater than the lengths of the steep, elevated waves believed here to be present in a rapidly building "over-driven" seaway. Figure 14 contains estimates of the increasing strength of the southwest wind during consecutive four-hour watches. It will be noted that between 1200 and 1600 hours the wind strength increased from SW 7-8 (32-46 knots) to WSW 11 (64-73 knots) and that the ship began "shipping seas over decks and hatches." During this interval, at 1450 hours the "vessel encountered mountainous swell" which caused the damage described in Figure 14. It should be noted that while the steep, elevated waves measured in Camille were not of unusual height with respect to the other large waves in the seaway, i.e. as measured from trough to crest, the elevated nature of the wave provides a somewhat different preception to an observer on a ship. The wave of Figure 11(c), for example, has a trough to crest height of 65 feet, but a height above mean water level of over 45 feet which could cause it to be regarded as "mountainous" among the other large waves of the seaway which were not steep and elevated. Characterization of the wave as "swell" is consistent with the long-crested nature of the wave as described by the officers from the ocean weather ships and as shown in Figure 12 and 13. The fact that the ship in question is long with respect to the distance between crests of such waves and that it has a relatively fine entry both suggest that it could have a tendency to penetrate into the wave and send substantial amounts of green water onto the foredeck and against the deckhouse provided that the wave was sufficiently large and elevated with respect to the ship's freeboard. (Model tests in steep, elevated waves would be required to reveal the true nature of this type of structural loading problem).

(3) U.S.S. SHREVEPORT (LPD-12)* DAMAGE INCIDENT

This casualty[1] involved the smashing of bridge windows by a large wave with ensuing personnel injuries. The reported time-series character of the damaging wave approximated that of Figure 11(c).[17] In this case the rate of build-up of the winds was less rapid than the two cases discussed above, although the winter storm was intensifying rapidly at the time. The peak winds were about the same as those encountered by the MARKET and were associated with a synoptic weather pattern also about the same (i.e. strong gusty southwest winds in a developing winter storm with the damaging wave being encountered shortly before frontal passage). Unlike Hurricane Camille, there was no conclusive evidence of large, steep, elevated waves appearing periodically in the seaway. The damaging wave was described by the Task Unit commander as "larger than usual" but not of extreme proportions considering the size of the other large waves in the seaway at the time. It was also characterized as "just breaking along its crest." This wave caused foreship damage including bridge window failures, bridge flooding, and a variety of local damage to watertight doors, gun tubs, a stairway, etc., which suggest a wave impact loading similar to that experienced by the MARKET.

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*Length = 570 feet, beam = 84 feet, displacement = 16,900 long tons.

(4) F/V FAIR WIND* CAPSIZE INCIDENT

This incident involves neither a ship nor significant structural damage. The wind and wave conditions which were responsible for capsizing this steel hulled, 52-foot fishing vessel, however, are of interest in characterizing the extreme waves likely to be associated with intense and rapidly developing wind fields.

The casualty occurred in the Georges Bank area off the Massachusetts coast during a rapidly developing winter storm (i.e., extratropical cyclone) on 22 November 1980. The storm intensified so rapidly that the severe wind and sea conditions which it generated were not forecasted and a number of fishing vessels were caught on Georges Bank in local winds of hurricane force. (This storm in fact subsequently became tropical and was named Hurricane Karl on 25 November).[18] The time rate of wind and wave buildup is reflected in the following information taken from the U.S. Coast Guard investigation:[19]

- 0800 hours 22 November, "The wind was NW, 50-60 knots, and seas were NW, 30 plus feet"

- 1130 hours 22 November, "The wind was NW, 80 plus knots, and the seas were NW, 50 plus feet."

An independent estimate of wind and wave conditions at 1300 hours was provided by the S.S. SEA-LAND PRODUCER, which was located approximately 45 N Miles east southeast of the casualty site, as "winds NNW at 78 knots and seas NNW at 40 feet." The fetch for NW and NNW winds in the casualty areas was approximately 230 N Miles.

The lone survivor (of the four men on the vessel) stated "and at eleven-thirty I, Billy was coming around so I just asked him if he would take the wheel for awhile and he was just on the wheel when we took an enormous wave and it broke onto the boat, it spun the boat 180 degrees and headed it back down the wave it seemed like it surfed down to the bottom of the trough and buried the nose of the vessel and the breaking water behind the vessel got under the stern and flipped it over end to end."[20] The wave conformation encountered by the FAIR WIND is believed to be represented (at least qualitatively) by that shown in Figure 12 in the area just forward of the starboard bow of the carrier, where the long-crested wave is breaking locally.

The nature of the steep, elevated waves postulated here to have been generated by the prevailing synoptic weather conditions is believed to be reflected in the following comment from a member of the crew of another fishing vessel in the area: "...and it seems to me that the peak of the wind in that storm was around anywhere from noon to two in the afternoon and I've never seen anything like it and we've been through plenty of 70-80 mph gales without any problem and I don't know if it was the tide, the time of the month when the tides were strong or not but it was pretty hard to estimate the height of the sea really, it depends upon how you measure it but I would estimate the sea from the trough to the height of it was

*Length = 52 feet, beam = 15 feet, displacement = 27 long tons.

70 foot,* it's awful hard to estimate but so we could't climb it, the SEA FEVER took two windows out."[19]

The unusual nature of the waves is attributed here to the development of steep, elevated waves in the rapidly rising wind field.

5.2 Encounters with Episodic Waves

Unlike the steep, elevated waves discussed above, the wave data of Hurricane Camille permit only a limited characterization of what has been termed here "episodic waves." Much of the information which permits characterization of such waves comes as a result of recorded wave encounters by ships as opposed to time-series wave height measurements. Those episodic waves which are aligned with the local seaway will be referred to as "Large, Grouped Waves". In the absence of time-series wave height measurements their classification as episodic is arguable, but since they are wave events which were easily remembered by the observers as being larger than the other waves in the prevailing seaway they will be characterized in this discussion as episodic. Waves which are distinctly misaligned to the local seaway and which cause extreme ship responses or structural loadings will be referred to as "episodic wave packets." Again the episodic character of the waves is inferred from the description of the waves and their effects on ships rather than time-series measurements of the waves.

5.2.1 Large, Grouped Waves

(1) U.S.S. INDEPENDENCE (CV 62)** Encounter with Large Grouped Waves

The CV-62 was part of a U.S. Navy task group which encountered a rapidly developing storm on [illegible] April 19[illegible] in the [illegible] Atlantic Ocean. Flight operations had commenced on the morning [illegible] when [illegible] change in weather began to occur at about 1130 GMT when, with the wind blowing [illegible] 25 KN from the northeast, the seas changed in 30 minutes from 8-foot seas from the northwest to 12-foot seas from the northeast with [illegible]. By mid-afternoon wind gusts reached 64 to 74 knots with [illegible] seas of [illegible] to 30 feet from the northeast.

At about 1600 hours the Captain [illegible] reported encountering a large wave group which he described as follows. "I looked out ahead, I'd estimate a mile to a mile and half, and I saw what appeared to me to be a significant wave coming, and I mentioned to somebody that this thing was just like the 'Poseidon Adventure', and the thing rolled in and I watched [illegible] and it was right at flight deck level where the rest of them had been [illegible] to 30, maybe a little over 30 feet, this baby was up around 55 to 60 feet [illegible] wave in front of it unfortunately...But when this wave [illegible] the started to plow in and it was coming down [illegible] just jarred the whole ship". Approximately 12 hours later [illegible] the [illegible]th, I had gone back to

*Presumably the height of [illegible] in view of the report from the S.S. SEA-LAND PRODUCER

**Length = 1047 feet [illegible] 5,000 [illegible] tons.

the at-sea cabin and we got hit by a wave that I have no idea how big it was, but it was by far the most severe jolt we had. And it just shook everything. The ship, you could feel the shock waves in it which kept up for an appreciable amount of time before it finally settled back down. Then at 7 o'clock on the morning of the 8th, I got the same thing I had the afternoon before. I saw a wave out about a mile, mile and a half, with a solid whitecap across the top which is what caught my attention. I watched it come all the way in at flight deck level, the same thing happened that happened the day before, lifted the bow and we were coming as we were coming into the second one. About 20 minutes later at 7:20, I got hit by another one, I estimate about 45 feet. Those are the four waves that in my estimation did all the damage." After that time "it was just a rough ride."

Thus one episodic wave group occurred at 1600 hours on the 7th, one at 0415 on the 8th (which apparently was the largest), and then two within 20 minutes of one another near 0700 on the 8th. The change in wind strength with time during the period was not given. Contained in the Findings of Fact[21] is the statement, however, that "the storm began to abate during the night of 8 April, but wind and seas remained high."

The time-series character of these wave events appear to be similar to the episodic waves of Figure 15, although obviously no firm conclusion can be drawn in the absence of time-series wave height measurements during the storm under consideration.

(2) S.S. SEA-LAND McLEAN* Extreme Hull Girder Bending Stress Measurements

On 19 December 1973, the SEA-LAND McLEAN proceeded down the English Channel in gusty winds of 30 to 35 mph. As it moved west bound into the North Atlantic the wind veered from south to west and finally northwest. The wind velocity dropped early-on as did the barometer so that at 0840 hrs (GMT) the wind was blowing 10 mph from the west with 5-foot waves at a barometric pressure of 28.68 inches of mercury. Two hours later at 1050 hrs the barometer had dropped slightly to 28.66 inches of mercury, but the wind had risen to 50 mph with an observed wave height of 25 ft. In successive two-hour intervals the wind rose to 70, 80, 90, and 100 mph (87 knots). At 1510 hrs with the wind at 80 mph, the ship was hove-to and remained that way for approximately 6 hours at which time a violent slam occurred (the peak stressing case), which prompted the captain to turn the ship around and run before the storm.

The midship bending stress trace corresponding to the extreme stress event is shown in Figure 16. While the wave-induced bending component shown in Figure 16(a) is larger than any other for the preceeding 1 1/2 hours, it was by no means episodic. The extreme nature of the stress event is largely the result of the slam-induced stress combined with it as shown in Figure 16(b). In this case, the dynamic stress is much larger than any other during the two-hour data analysis interval. In general, the ship showed very little tendency toward slamming although lateral whipping was relatively frequent. During the stressing event in question, a large lateral slam stress was induced approximately 1.6 seconds after the apparent bottom slam. The vertical accelerometer at midships indicated that each loading was of an impulsive nature.

*Length = 946 feet, beam = 106 feet, displacement = 47,700 long tons.

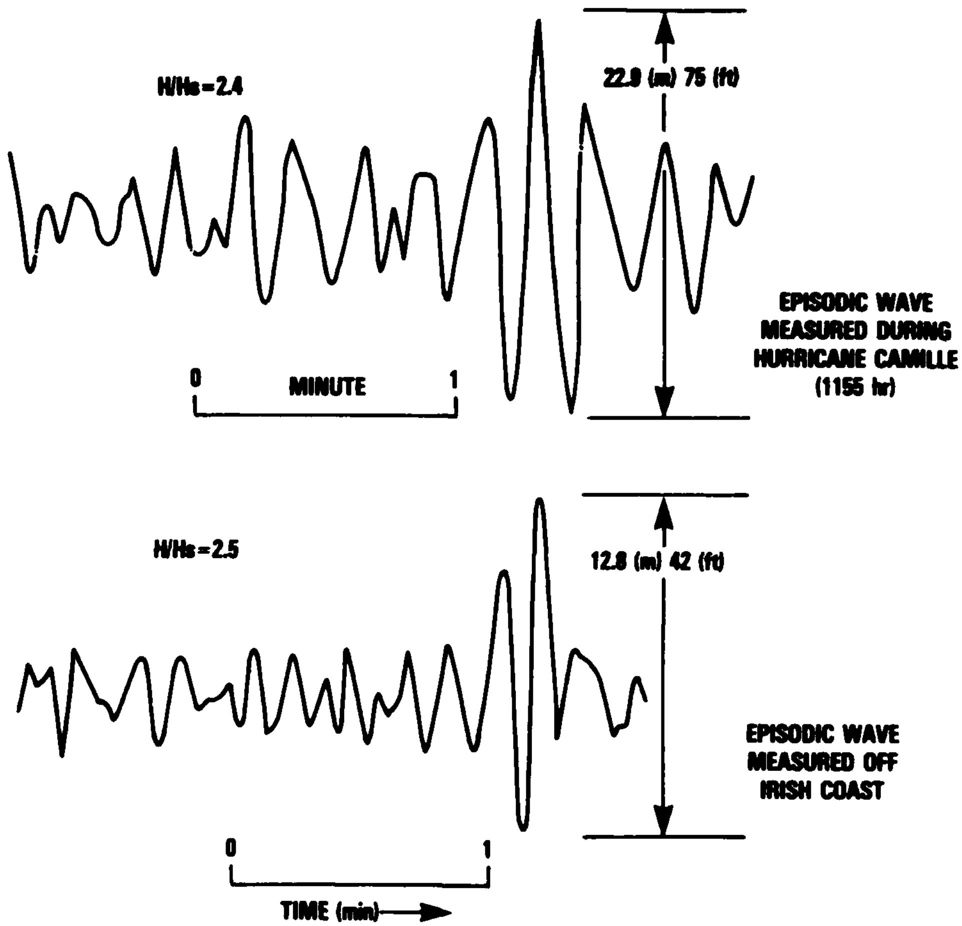

Figure 15 - Time-Domain Similarity of Episodic Waves from Different Storms

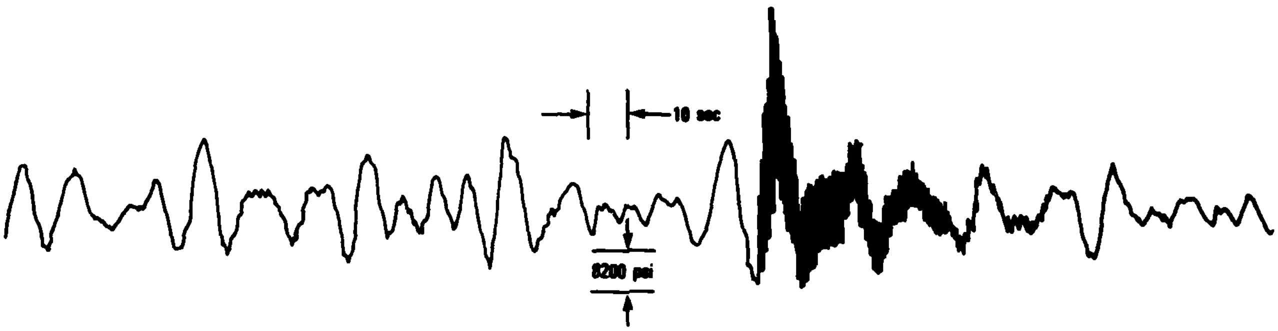

Figure 16a - Wave Induced Longitudinal Vertical Midship Bending Stress
(Average of Port and Starboard)

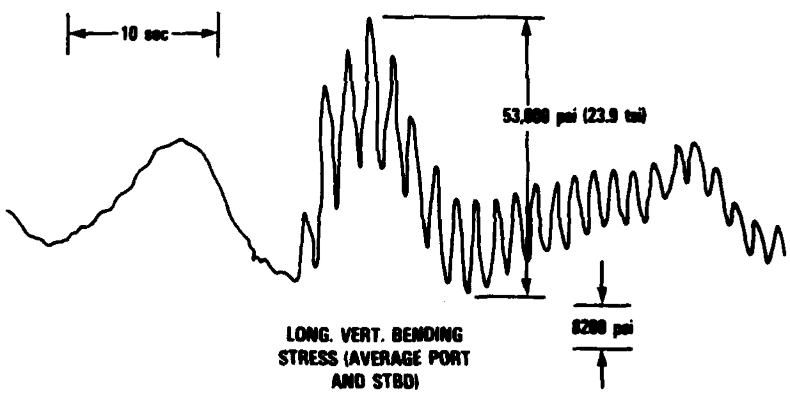

Figure 16b - Expanded Time Scale Showing Combined Wave-and Slam-Induced Stresses

Figure 16 - Extreme Hull Girder Bending Stress Measured on S.S. SEA-LAND McLEAN During Winter Storm

No wave height measurements are available for the data analysis interval, nor were visual descriptions available, so that the true character of the wave height time-series can not be determined. The time-series of the wave induced bending trace (Figure 16(a)), however, suggests a sequence in which a large wave was followed by an even larger wave and that the latter induced heavy slamming. This sequence of events is similar to that which resulted in heavy slamming of the CV-62 as described above and it is believed reasonable to conclude that large, grouped waves were the cause of this extreme stress event. No conclusion can be drawn, however, as to whether the wave group was of an episodic nature. The wave-induced bending trace, in fact, implies that it was not.

(3) U.S.S. FAIRFAX COUNTY (LST-1193)* Observation of Large, Grouped Waves

The damage incident involving the LPD-12, which is reviewed in Section 5, caused that ship, and the LST-1193 which was in company with it, to turn and proceed before the storm. During this latter phase of the storm, i.e., well after frontal passage, a watch officer on the LST testified as follows:

"The barometer was steady, wind was from approximately 260-280 at 40-45 kts. During this watch, the barometer rose at a rate of about 0.02 hour, the wind veered to the West/Northwest and decreased to 28 kts. The seas when I assumed the watch were an average height of 30-40 feet. In addition, about every ten minutes, a series of three waves of approximately 60 feet in height were observed. I reached my estimate on the height of these waves based on the fact that their crests were higher than my height of eye from the bridge which was 54 feet. Also, whenever the ship experienced a large wave series, she would pitch to the point of appearing to "surf" down the wave face. On several of these occasions, I specifically noticed that the derrick arm cross-walk, appeared from the bridge to be about 10 feet below the wave crests."[17] The officer in question, when interviewed later stated that the reoccurring groups of three large waves were observed for a period of about 2 hours out of his 4 hour watch.** The time-series character of the waves could not be described with certainty because they approached from astern. The officer had no recollection of the second wave in the group being substantially larger than the preceding and following waves of the group. Based upon the ship orientation when surfing down the waves, the distance between wave crests was believed to be significantly greater than the ship length of 522 feet.

In this instance no ship damage or extreme motions resulted from the encounter with these large, grouped waves, although steering difficulties caused them to be easily remembered. This case is cited here because of the periodic appearance of the wave groups under the existing synoptic wind field conditions which will be considered further in Section 6.

5.2.2 Episodic Wave Packets

Waves of this type appear to be associated with relatively unique synoptic weather conditions. With the exception of the wave data of Figure 15, their time-

*Length (hull) = 522 feet, beam = 70 feet, displacement = 8342 long tons.

**Since the ship was proceeding at 14 knots before the sea, this time period is longer than would have been noted by a fixed observer.

series characterization is confined to the qualitative descriptions by ship's officers and masters which are presented in Section 4. The long period (i.e. long wave length) characterization appears to be reasonably well established, as well as their tendency to arrive misaligned to the local seaway. This latter characterization is of considerable importance since it suggests that they are generated in a remote wind field and that they are necessarily of a non-dispersive nature.

(1) M/V CHU FUJINO Wave Damage Incident:[22]

The M/V CHU FUJINO is a 127,000 ton bulk carrier 856 ft long, 133 ft wide, with a summer draft of 57 ft, 9 in. It has a flush deck with bridge aft. On December 28, 1979, while proceeding fully loaded from Los Angeles to Japan in a severe winter storm, it encountered an episodic wave which caused localized loss of watertight integrity of a serious nature. The ship was proceeding at a speed made good of about 1 knot on a course of 250°T with seas about two points (22.5°) off the starboard bow. Winds had increased to 75 knots producing observed wave heights of 30 to 60 ft with estimated periods of about 8 to 10 seconds. At about 1540 hours (local) the ship was struck by a single wave estimated to be about 100 ft in height. The ship's position was 34-30N, 150N at this time. The wave approached from about 70° off the starboard bow and thus at an angle approaching 45° to the prevailing seaway. Damage consisted of the following:

"Stbd bridge windows smashed in. Stbd lifeboat washed away and davits flattened to deck. Two stbd aft liferafts and foredeck liferaft washed away. Sailing dinghy fwd of bridge smashed against port crane. Wing/ballast tank vents damaged, baffle plates washed away, floats fell out, and wing tanks flooded. Bolted engineroom access plating on deck fwd of bridge buckled and was torn loose, allowing water entry to engineroom. Foc'sle storeroom; fwd pumproom; No. 1 and No. 2 double bottoms, port and stbd; forepeak tank - all completely flooded. Some water in No. 3 topside tank stbd."[22]

Because of the engine room flooding the ship was totally without power and hence steerageway for over an hour. Flooding forward was such that the ship became 25 ft bow down by 0130 hours on the 29th, with the fo'c'sle awash. At this point the Captain radioed for U.S. Coast Guard assistance; however, the seas abated sufficiently by morning that the flooded spaces forward could be pumped out and the ship proceeded safely to Honolulu for repairs.

The following aspects of the damaging wave are believed to be of particular interest. The reported swell heights of 30 to 60 feet are interpreted to mean that 60 ft was the height of the highest waves at the time. The significant wave height would then be estimated to be about 60/1.65 or 36 ft which is close to the lower value cited. For this significant wave height, a truly episodic wave would be estimated to be 2.4* x 35 to 2.5 x 35 = 84 to 87.5 ft high which is slightly less than the reported value of 100 ft. In the absence of clarifying comments, the wave would appear to be a single event although this is not certain.

Discussion of this incident will be deferred to Section 6.

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*Based upon the characteristics of the episodic waves shown in Figure 15. The use of these ratios must be regarded as entirely speculative at this time.

(2) M.V. MUNCHEN* Sinking:

This German-owned LASH ship was lost with all hands during a winter storm in the North Atlantic in December 1978. Because of radio transmission failures no eyewitness details regarding wave characteristics or ship damage are available. The findings of the subsequent Sea Court inquiry which are of primary interest here are that sometime not long before 0310 hrs GMT on 12 December at a location approximately 100 NMi south southeast of location 46° 15' N, 27° 30' W the MÜNCHEN was struck by an extreme wave from forward and to starboard with attendant damage which led to the ship's foundering on the 13th.

The particulars of their findings included the following:[23] "The fact that, as detailed by the experts Sandomeer and Dr. Pavlides, the starboard lifeboat, without being used, was torn out of its securings, speaks for the fact that the MÜNCHEN was hit from forward by one or more enormous seas on the starboard side. This striking sea - with great probability - also caused heavy damages in the bridge area. This must have resulted in water ingress and subsequently in a starboard list, possibly up to 50°. Speaking also for this is the, likewise garbled, distress call relay report from the MARIYA ERMOLOVA. The water ingress must have led in shortest time to the breakdown of the main power supply of at least the W/T sphere. It must also be supposed that the antenna system of the MÜNCHEN suffered such heavy damages that it was no longer functional. The Seeamt is convinced that the SOS call of the MÜNCHEN received by the MARION was transmitted with the battery-driven emergency transmitter with reduced output. Because no other message was received from the MÜNCHEN after the SOS calls at 0310 hours GMT and 0315 hours GMT on 12 December 1978, the Sea Court has come to the conviction that the emergency transmitter also broke down. Probably the lifeboat transmitter held on the navigation bridge had also previously been made unserviceable by striking seas.

"The Seeamt also gave thought as to what the word "Articas" could have meant, which was transmitted and received by the MARIYA ERMOLOVA. The most plausible explanation is seen by the Seeamt as being possibly an error in reception by the Russian radio officer, who did not clearly understand the word "antenna" and interpreted it as Articas.

"Based on the result of the testimonial evidence the Seeamt is of the opinion that the MÜNCHEN did not sink before 1100 hours GMT on 13 December, 1978. This conclusion is justified as the signals from the radio distress buoy were first heard at this point of time by several stations, although other ships, also beforehand, were in the possible receiving range of the buoy.

"The interrogation of the experts Dr. Pavlides and Sandomeer elicited the information that both salvaged lighters left the parent ship longitudinally. This speaks decisively for the MÜNCHEN having foundered without having a severe list and being out of trim. From this follows, also, that the MÜNCHEN cannot have been broken by failure of the longitudinal members or have capsized from insufficient stability."

Discussion of the incident will be deferred to Section 6.

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*Length = 858 feet, beam = 100 feet, displacement = 37,000 long tons.

(3) U.S. NAVY FRIGATE Wave Damage Incident:[24]

This FFG-7 class* ship, while proceeding south on 12 February 1982 off the Oregon coast, encountered an episodic wave of relatively small proportions. The first wave of the two successive waves which were encountered (about 5 seconds apart) was estimated to be approximately 30-ft high with the appearance of a "wall of water." The first wave destroyed one bridge window and heavily damaged another. (The windows were judged by personnel on the bridge to have been hit by aerated rather than solid green water.) Bulwarks forward were flattened with some local loss of watertight integrity where supporting members were pulled from the deck.

The waves at the time were described as being 10-to 12-ft high with a 7-to 8-second period at a bearing of 220°T. The local wind strength was estimated to be 25 knots and gusting from the west. The ship heading was 190°T. The episodic wave approached from 20° off the port bow which placed it at an angle of approximately 50° to the local seaway. The ship's barometer recorded 29.45 inches Hg (993 mb) one hour before the incident and 29.64 inches Hg (1004 mb) one hour after with a wind shift from west to northwest and an increase in strength from about 25 to 38 knots.

The approximate 11 ft significant wave height of the existing seaway when multiplied by a ratio of extreme wave height to significant wave height of 2.4-2.5 to 1 would suggest an episodic wave height of approximately 26 to 27.5 ft. This height range is relatively close to the observed wave height of 30 ft.** The approach of the wave at a substantial angle to the local seaway is believed here to be characteristic of this type of wave event based on the casualty information presented above and the previous comments of ship masters et. al. regarding extreme wave packets.

The damage trends are quite consistent with cases described above in the following respects:

(a) No hull girder structural integrity problem occurred. Damage was due primarily to local wave impact loadings and was dangerous mainly because of associated losses of watertight integrity.

(b) Window failures occurred. This result is similar to that involving the LPD-12 to the extent that it involved window damage as a result of water thrown against the bridge upon encountering a large, steep wave, and further that window failure occurred without substantial damage to the supporting bulkhead structure.

6.0 DISCUSSION

The following discussion considers the possible origin of large, non-Gaussian and episodic waves and of their potential effects on ships.

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*Length = 445 feet, beam = 45 feet, displacement = 3710 long tons.

**Based upon the characteristics of the episodic waves shown in Figure 15.

6.1 Origin of Large, non-Gaussian and Episodic Waves

Much of the information presented in this report regarding such waves is circumstantial, as opposed to information obtained by direct measurement under known or controlled conditions. Notwithstanding this serious limitation, the observations and generalizations which follow are put forward in the spirit of an initial effort to describe and understand the origin of large, non-Gaussian and episodic waves.

Table 2 is a summary of the information presented in Section 5 which has been used to characterize the waves discussed in that section. The following additional comments are offered.

6.1.1 Steep, Elevated Waves

The appearance of waves of this type during Hurricane Camille, when the ambient wind velocity was rising rapidly together with the circumstantial evidence of the casualty cases cited above, are believed to provide justification for anticipating the existence of such waves under the associated synoptic wind field conditions. Two qualifications of this generalization should be noted however. First, the episodic wave which occurred at 1222 hours during Hurricane Camille indicates clearly that such waves can occur (at least in an isolated case) under other wind field conditions. Second the half-cycle analysis of wave data between 1530 and 1600 hours,[2] as well as unpublished data for the period 1600 to 1617 hours, shows a less distinct trend toward positive mean elevation among the larger waves in the seaway. At this point in the storm, there is an evident tendency toward a more broad-band, Gaussian character to the larger waves in the seaway. There is insufficient wave data to permit generalization but it is possible that wave characteristics began to undergo further change near the eye of the hurricane.

The long-crested nature of the steep, elevated waves is regarded as surprising given their elevated character and the obvious possibility that they could result from the overtaking of one wave by a larger and faster wave in a seaway dominated by short-crested waves. An alternative possibility is postulated by Yuen and Lake[25,26] who discuss "non-linear coherent" wave models.

They state:[25] "Traditionally, a wind-wave system has been regarded as a basically linear incoherent superposition of free infinitesimal wave components; all components obeying the dispersion relation and propagating with different speeds. Effects of nonlinearity have been calculated based on these assumptions. We refer to these traditional models as near-linear incoherent models (see for example, Hasselmann 1962, 1963, 1967). More recently Lake and Yuen (1976)[26] have proposed a drastically different model, which postulates that wind-wave systems can be basically nonlinear and coherent. When a wind-wave system is nonlinear in this sense, the effects of nonlinearity on the dynamics of the system are predominant over the effects of randomness. In its simplest form, a one-dimensional context,* such a wind-wave system can be characterized to first order by a single nonlinear wave-train having a carrier frequency equal to that of the dominant frequency in the wind-wave spectrum. We refer to this model as the nonlinear coherent model.

*That is, infinitely long-crested, waves.

TABLE 2 - AN INITIAL CHARACTERIZATION OF LARGE NON-GAUSSIAN AND EPISODIC WAVES

TYPE	CHARACTERIZATION	BASIS FOR CHARACTERIZATION
I. Steep, Elevated Waves	• Steep and elevated above mean water level • Period as low as 70% of modal period • Elevation/amplitude ratio ≈ 0.5 • Produced by strong, rapidly increasing winds • Long-crested (see figures 12 and 13)	• Time-series wave data from Hurricane Camille (see Figures 9(b) and 11) and associated wind velocity increase. • Casualty cases associated with strong rapidly increasing winds: - SEA-LAND MARKET - LPD-12 - CHESTER A. POLING - F/V FAIR WIND • Observations by officers from ocean weather ships
II. Episodic Waves*		
a. Large Grouped Waves	• Group of three large waves in seaway. Second wave frequently largest in group. • Occur in storm winds which are no longer increasing, or which have begun to decrease.	• Waves encountered by CV-62 SEA-LAND McLEAN, LST-1193
b. Episodic Wave Packets	• "Three Sisters": group of three long-period waves intruding into existing seaway at angles of about 30 degrees from principal wave direction. Generally occur in vicinity of storm with central winds of 60 knots or more.	• Observations by officers from ocean weather ships as well as ship masters of considerable at-sea experience
	• "Rogue" Wave: large breaking wave intruding into existing seaway at angles up to 50 degrees from principal wave direction. Likely to occur in vicinity of upper altitude "TROF" as it overtakes an existing or developing low. High altitude comma shaped cloud usually associated with TROF.	• Rogue Wave encounters by U.S. NAVY FRIGATE, CHU FUJINO, MÜNCHEN, and associated synoptic weather patterns.

*Note: These characterizations do not necessarily apply to waves in Agulhas current (S.E. Coast of Africa).

"The main difference between the two models lies in their respective predictions regarding the properties of relatively high modes. The near-linear incoherent models would predict that all wave components are free and obey the dispersion relationship, and hence travel with different speeds. On the other hand, the nonlinear coherent model would have the higher modes phase-locked to the dominant wave, and hence traveling with the speed of the dominant wave." [This characteristics is postulated from properties of wind waves generated in a test tank.]

"Lake and Yuen (1976) have performed laboratory experiments to test the predictions of these models against laboratory measurements of wind-generated waves. In one series of measurements they bandpass-filtered the records from pairs of closely spaced probes and used cross-correlation techniques to determine the propagation speeds of individual wave components. Their results, which are in complete agreement with independent measurements made by Ramamonjiarisoa and Coantic (1976), demonstrate that under laboratory conditions wind waves are nonlinear in the sense of the nonlinear coherent model since all higher modes travel with a single speed - the speed of the dominant wave."

The major finding of the experiment was that the higher frequency energy in the wind wave system was transported at the group velocity of the dominant waves rather than at speeds predicted by the linear wave dispersion relation. The dominant waves thus tend to collect energy from the smaller waves in the seaway. Since the dispersion relation for linear waves* causes waves of different wave length to travel at different speeds, it helps to account for the basically random character of a wind driven seaway. Evidence that the dispersion relation is violated under some conditions is therefore of considerable importance when attempting to account for the existence of "non-Gaussian" waves.

As applied to the situation at hand, the postulations of Yuen and Lake have certain difficulties which should be noted here. During Hurricane Camille, a half-cycle analysis of the wave data identified non-Gaussian and episodic waves and found that such waves were very much *in the minority, i.e.*, even when they occurred the seaway was still predominately Gaussian and that when the steep, elevated type of wave began to appear, the seaway was only "over driven" by a factor of about 50/34 = 1.5.** In the laboratory experiments of Yuen and Lake the test wind speed was on the order of 20-35 ft/sec[26] while the modal period reported was 1/3 Hz = 0.33 sec. which would correspond to an average wind speed of only about 0.8 ft/sec for a fully developed sea of this modal period (see Figure 7(a)). The seaway in the test tank was thus overdriven by a factor of about 28/0.8 = 35 which is well removed from the wind-sea conditions of Hurricane Camille.

These observations are not considered to detract from the importance of the laboratory experiment, however, which shows that the linear wave deep water dispersion relation governing wave propagation speeds can be substantially violated in the generation of wind waves. If the tendency of the dominant waves to collect

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*$\omega = \sqrt{gk}$ where ω = frequency of the harmonic constituent, and $k = 2\pi/\lambda$ where λ = wave length, and g = gravitational constant.

**Ratio of existing average wind speed to that which would produce a fully developed seaway having the existing modal period energy from the smaller waves is primarily a function of the steepness of the larger waves, then the fact that the test seaway was substantially overdriven may not be of great importance.

6.1.2 Episodic Waves

Table 2 identifies large, grouped waves as one broad category of episodic wave and episodic wave packets as another. The discussion which follows deals almost exclusively with the latter based on the presumption that an understanding of its origins is likely to provide an understanding of the origin of the former.

The observed characteristics of episodic wave packets (see Sections 4 and 5 imply certain properties of these waves which appear remarkable at this point. The first relates to the apparent non-dispersive quality of the waves which is implicit in the appearance of a packet of waves from a direction substantially inclined to the local wind field and seaway. The energy of the wave packet has evidently remained intact over a considerable distance, at least in terms of the lengths of the waves involved. The second remarkable quality is that the waves are very large with respect to the local seaway which implies the existence of very strong winds substantially inclined to the local wind field somewhere upwind in the storm. Since the wave packet cannot be expected to be infinitely long-crested, it could never be truly non-dispersive.*

A physical distance over which the packet could be regarded as essentially non-dispersive is likely to be small in terms of the distance associated with the wind field of a winter storm. A distance on the order of 10 to 50 miles, for example, is small with respect to the distances over which substantial changes in wind direction normally occur in a major storm (excluding the area near the center of the storm for the moment). The appearance of a large mis-aligned wave packet thus appears to require a wind field characteristic almost as unusual as the non-dispersive wave packet itself.

6.1.2.1 Non-Dispersive Wave Packets. Waves of non-dispersive character have been known to be possible in shallow water for well over 100 years. It is only in the last 15 years, however, (beginning about the time of the analyses and experiments of Benjamin and Feir[27]) that the non-linear properties of deep water waves have been studied at length. As the result of these studies the existence of deep-water non-dispersive waves has been predicted and demonstrated in a small test tank. An excellent overview of these developments is provided by Phillips.[28] Of particular interest here is the work of Yuen and Lake[29] who demonstrated (again in a small tank) the non-dispersive nature of deep-water "envelope solitons", which had been predicted earlier as the result of a solution of the non-linear Schrodinger equation.[29] The experiments further demonstrated properties of a wave packet which will be termed here the "imperfect soliton wave packet" that is of considerable importance given the very specialized nature of the envelope soliton, namely, a wave group of uniform period having a modulation envelope corresponding to the hyperbolic secant. Since it is extremely unlikely that in nature long-crested wave packets of

*Because of amplitude dispersion. For waves of finite amplitude $\omega = \sqrt{gk}\,[1 + 1/2\,(ak)^2]$, where a = wave amplitude. Thus the center of a short-crested wave can be expected to travel faster than the outer (lower) portions and hence cause the wave to disperse.

this precise description are ever generated by a wind field, the fact that the imperfect* soliton wave packet was both predicted and demonstrated to be stable to the extent that it reforms to an idealized packet of fewer and higher waves is of considerable practical importance. The evolution of the imperfect soliton wave packet to fewer and higher (and necessarily steeper) waves is interesting in view of the existence of "rogue" waves which could thus be explained in part as the breakdown of an imperfect soliton wave packet which was never so well formed initially as to permit the evolution of a stable packet.

Such a possibility is, of course, pure speculation at this point. In fact, no explanation is suggested here as to a mechanism by which wind can generate even an imperfect soliton wave packet. The possible development of long-crested waves in a seaway, which is clearly a condition for the existence of the soliton wave packet, is nevertheless suggested by Yuen and Lake[25] above and certainly by the large waves of Figures 12 and 13. The existence of large, grouped waves (see Table 2) further suggests that the packet could have its origin under wind field conditions which produce this type of episodic wave group.

While modern developments in non-linear wave mechanics do not provide a completely satisfactory explanation of the origin of episodic wave packets, it is suggested here that they provide an initial foundation.

As noted under Section 6, the existence of episodic wave packets implies the existence of a storm-related wind field of considerable strength with a spatially abrupt change in direction. The research of Sanders and Gyakum[30] provides evidence of the existence of the inferred wind field as part of a broader study of rapidly developing winter storms which they characterize as the "bomb."

For purposes of their research the authors define a "bomb" as a rapidly developing extratropical surface cyclone (typically a winter storm) whose central pressure decreases 24 mb or more in a 24-hour period. They investigated storms meeting this criterion during the period September 1976 to May 1979 as to their characteristic development, location, and frequency, and to a lesser degree the surface wind field development which is the characteristic of prime interest here.

With respect to characteristic development, they find that the overtaking of a surface low by a faster moving, upper altitude TROF** generally precipitates "bomb" development. This condition can usually be identified by comparing the surface weather map, which locates the low, to the corresponding map drawn for a pressure altitude of 500 mb, i.e. approximately 18,000 ft, which best identifies the approaching TROF. As the storm intensifies, the region of strong and rapidly shifting surface winds associated with the TROF (now a major surface event) is usually evidenced by a major "head cloud"[30] or "comma shaped" cloud[31] as seen in satellite photographs of cloud formations. As characterized by Reed,[31] the head of the comma-shaped cloud will generally lie near the center of the low, while its trailing edge will mark the axis of the TROF. Because of the relatively higher speed of the TROF,

*Imperfect with respect to the modulation envelope only in the Yuen and Lake experiments.

**Typically a region (or band) of low pressure connected to a surface low and having U- or V-shaped isobar contours.[31]

it will frequently overtake and pass the occluded cold front. In addition it is not uncommon for a new TROF to form behind the original one as illustrated by Reed.[31] (See also discussion of M/V CHU FUJINO episodic wave encounter in section 6.

A relatively dramatic example of the strong and abruptly angled surface wind field associated with "bomb" development is shown in Figures 17(a), (b), and (c) which are taken from Sanders and Gyakum.[30] Early development of the storm at 00 hours GMT on 4 February 1975, Figure 17(a), shows essentially routine cyclogenesis with the exception of a wind vector near 40 N, 65W which indicates locally observed 60 knot winds from the west in contrast to the adjacent vectors which indicate winds of only 20 to 25 knots. Figure 17(b) shows that 12 hours later the central pressure has dropped abruptly from 1000 (29.5 in. of Hg) to 968 mb (28.5 in. of Hg). Winds have generally increased and locally high winds of 45 and 60 knots are now observed near 40 N, 50-60 W. The presence of the TROF is clearly in evidence 12 hours later as shown in Figure 17(c) where the high curvature of the isobars show it extending southward from the center of the low. The central pressure is now 944 mb (27.8 in. of mercury) with local winds of 50 to 60 knots. Two wind vectors along 45 W in the vicinity 45 N identify a local region with winds of 75 to 60 knots from the north. The isobar pattern in the region of the TROF shows nearly a 90 degree change in direction along the isobar at which these high winds are reported. The anomolous character of the wind field is further indicated by the fact that 6 isobars (48 mb or 1.4 in. of mercury) removed from the center of the low, winds of 75 knots are reported in contrast to the central winds of 50-60 knots. Because of the lack of ship observations near the TROF, particularly in its eastern half, the spatial abruptness of the wind shift is open to speculation.

Figure 18 illustrates the usefulness of satellite photographs in identifying the presence of a TROF by the existence of the associated "comma-shaped cloud". The TROF at this stage of storm development is aligned with and close to the trailing edge of the comma cloud and again the region of abrupt wind shift coincides with the axis of the TROF. Strong winds are reported locally (see 1008 mb isobar), this time immediately to the east of the axis of the TROF. Again the available ship observations do not permit an adequate mapping of the rapidly changing strength and direction of the wind field in the vicinity of the TROF.

6.1.2.2 <u>Ship Damage Incidents Involving Episodic Wave Packets.</u> At the present time no well documented encounters with episodic wave packets of the "three sisters" variety are available for analysis presumably due to the fact that, while encounters with them produce severe rolling, they do not necessarily result in major structural or other noteworthy damage. The episodic wave packets of Figure 15 provide time-series data which have ratios of maximum wave height to significant wave height of 2.4 and 2.5 to 1 which may well be representative. There is no basis, however, for concluding whether or not the wave packets involved were misaligned to the existing seaway. If they were, then of course the time-series data of Figure 15 could be a valid tim^ series characterization of the "three sisters."

Whereas wave packets of this type have not resulted in notable damage incidents (within the scope of this study), the opposite is true of "rogue" waves. In section 5 above, three damage incidents known or believed to have been caused by "rogue" waves were summarized. These incidents will now be examined further.

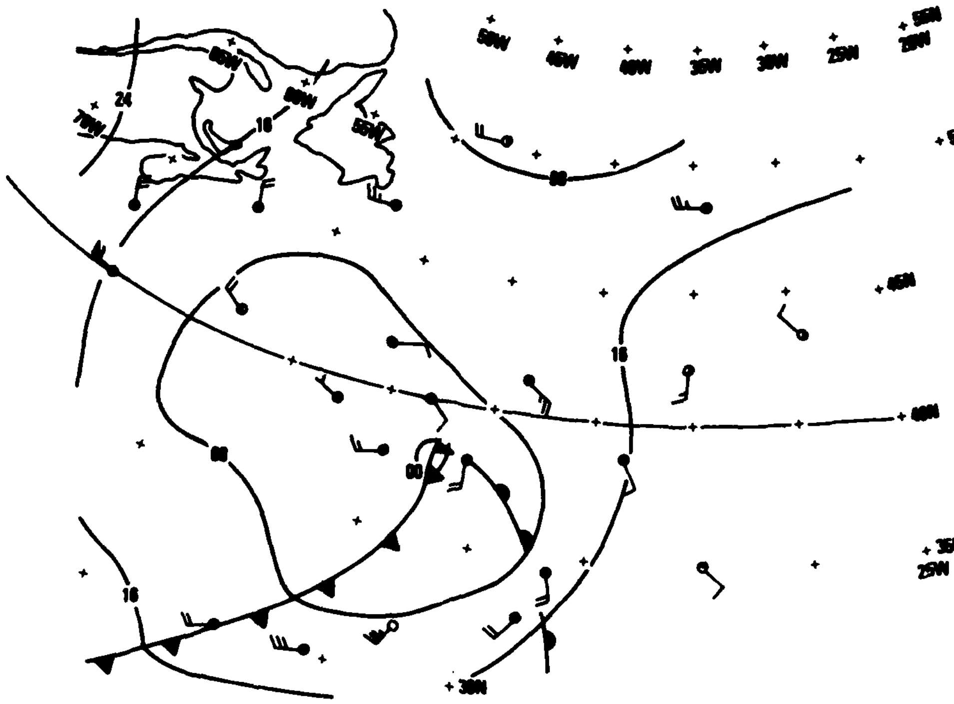


Figure 17a - 4 February 1975; 0000 GMT

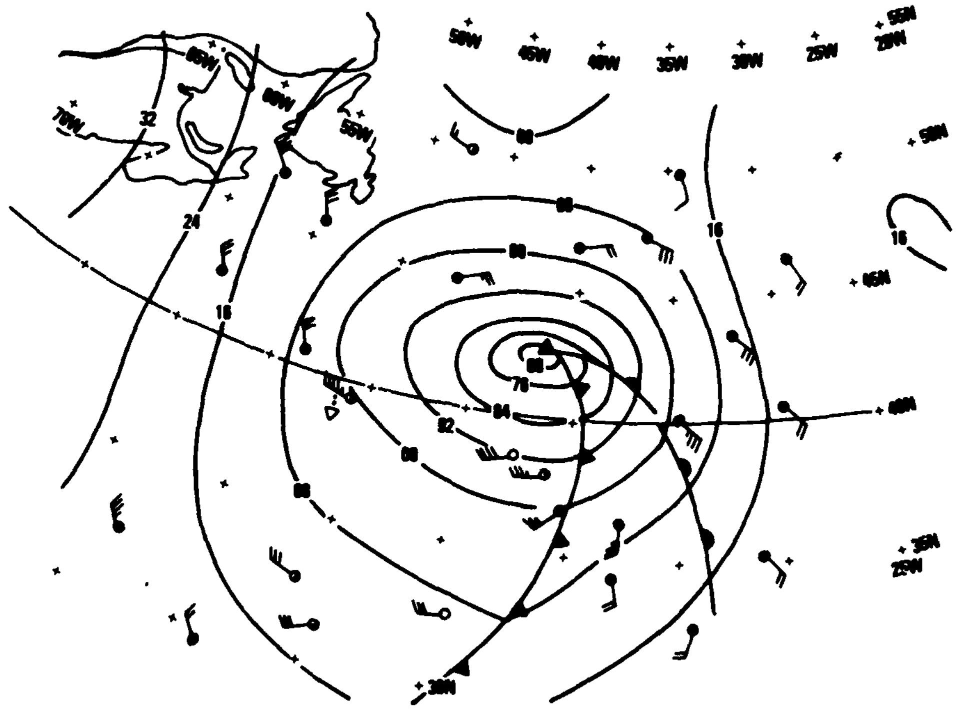


Figure 17b - 4 February 1975; 1200 GMT

Figure 17 - "Bomb" Development as Illustrated by Sanders and Gyakum
(From Figure 1 of Reference 30)

Figure 17 (Continued)

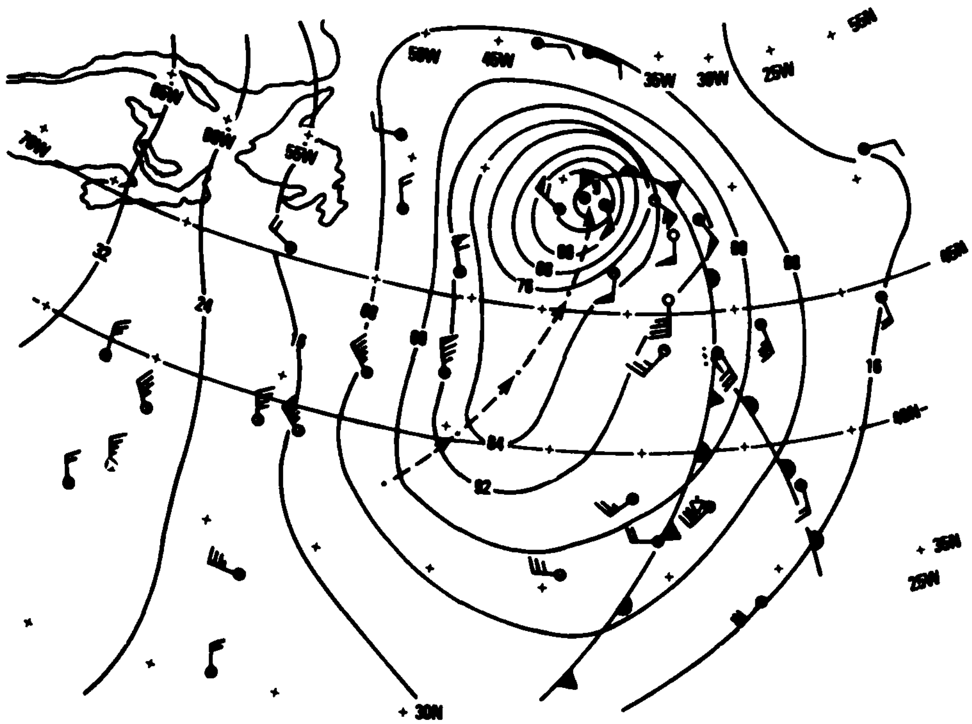
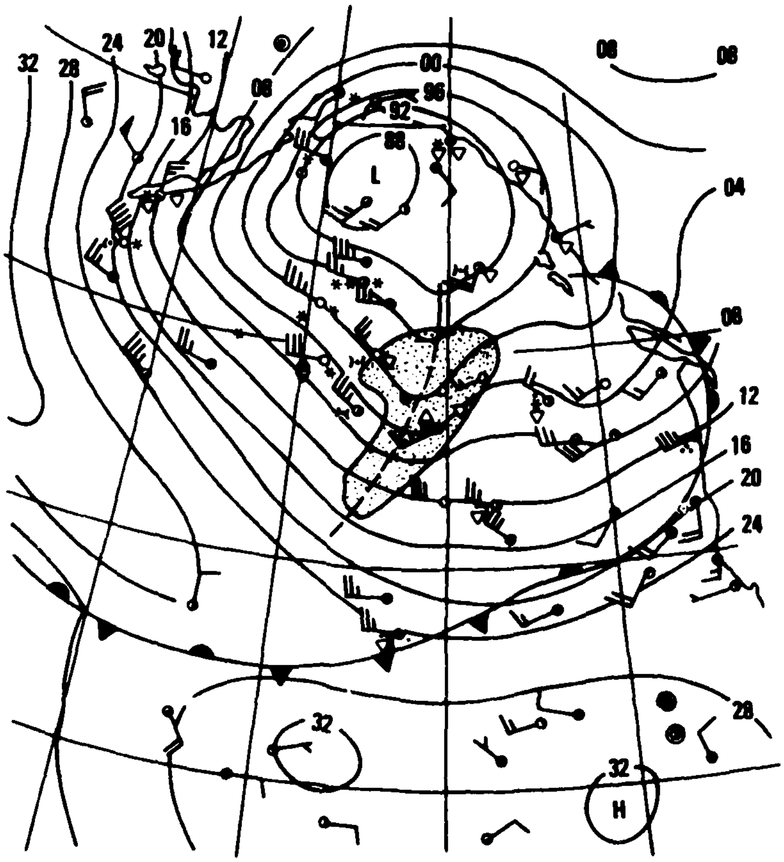


Figure 17c - 5 February 1975; 0000 GMT



NOTE: SURFACE WEATHER MAP FOR 24 FEB 1976; 1800 GMT – STIPPLING DENOTES CLOUD SYSTEM.

Figure 18 - Relationship of TROF in Winter Storm to Cloud Pattern as Illustrated by Reed (From Figure 8 of Reference 31)

(1) M.V. MÜCHEN Sinking

The ship casualty was believed by the investigating court to have been precipitated by the MÜNCHEN being "hit from forward by one or more enormous seas on the starboard side."[23] The discussion above suggests that such a "rogue" wave event might involve the wind field associated with a TROF in a winter storm.

Surface weather maps appropriate to the time and location of the casualty are presented in Figure 19. It is apparent that no indication is given of an abruptly changing wind field. Figure 20 on the other hand shows that a comma-shaped cloud has formed and passed over the casualty site near 0600 hours which infers that a TROF was encountered at about the time of the distress message. Since the cloud formed and moved eastward from longitude 35 W to 20 W (i.e. approximately 46 x 15 = 690 N Mi) in 12 hours, its speed of eastward movement was approximately 58 knots. The rate of formation of the cloud into the comma-shape characteristics of the early development of a surface TROF was also very rapid. Unlike the cases of cyclogenesis studied by Sanders and Gyakum,[30] the low overtaken by the TROF here was already an intense winter storm having a central pressure of 968 mb (28.6 in. of mercury) at 1200 GMT on the 11th. It intensified at 0001 GMT on the 12th to 952 mb (28.1 in. of Hg) near the time of the initial casualty.

The Mariners Weather Log's listing of Selected Gale and Wave Observations, North Atlantic for November and December 1978[32] contains additional evidence of the passage of a TROF. The EXPORT PATRIOT, whose position is noted in Figure 19(a) and (b) (the only times for which data were given) was slightly west of the MÜNCHEN at 0001 GMT on the 12th. It reported winds of 55 knots from 270 degrees at 1800 hr GMT on the 11th and 55 knots winds from 230 degrees at 0000 hrs on the 12th. The surface air temperature had also dropped from 12° to 7°C during the interval, further suggesting passage of the TROF indicated in Figure 20. The seas at 1800 hrs were reported by the EXPORT PATRIOT as 29.5 ft while at 0000 hrs they were reported as 39 ft.

Although no firm conclusion can be drawn regarding the likelihood of a "rogue" wave having existed at the initial casualty site based on this information, the foregoing observations are nevertheless believed to be supportive of the Maritime Court's belief that the MÜNCHEN was struck "by one or more enormous seas".

(2) M/V CHU FUJINO Wave Damage Incident

TTT The surface weather maps related to the MÜCHEN casualty, Figure 19 and the corresponding maps for the episodic ("rogue") wave encounter by the CHU FUJINO, O of Figure 21 show considerable similarity. The comma-cloud pattern of Figure 22(a), however, was well developed some 24 hours before the damage incident in this case. Moreover, the surface analysis map of Figure 22(b) when compared to the cloud pattern shows that the TROF had already overtaken the occluded cold front at that time. The projection of the motion of the storm during the next 24 hours shown in Figure 22(a), suggests that the CHU FUJINO encountered a second and smaller TROF-like wind field originating at the head of the comma-shaped cloud by 0140 GMT when the episodic wave was encountered. The cloud pattern and surface weather map in this case are very similar to those found by Hamilton to be associated with the capsizing of NOAA Data Buoy EB-21 on 2 January 197[illegible] at 46 N 136 W. In general he finds four capsizings to be associated with the passage of a TROF located near the center of the

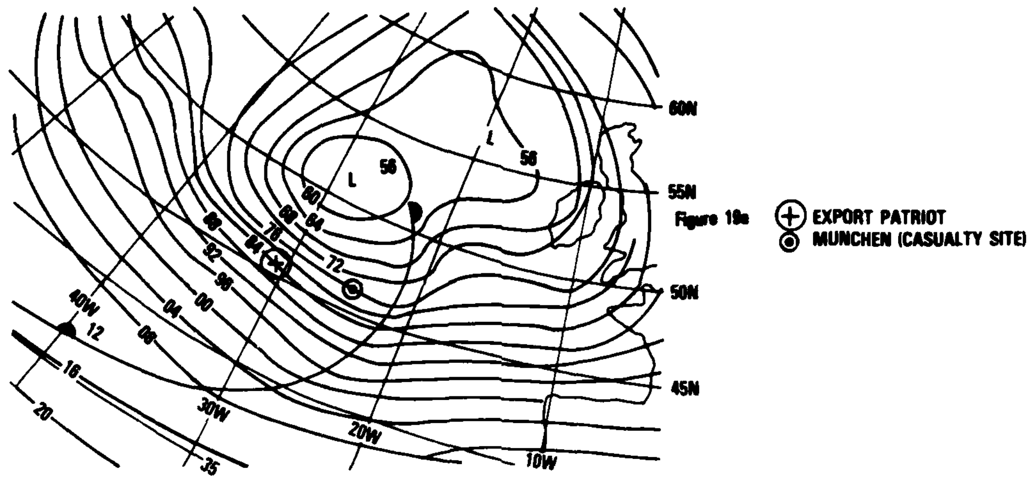


Figure 19a - Surface Weather Map for 11 December 1978, 1800 GMT

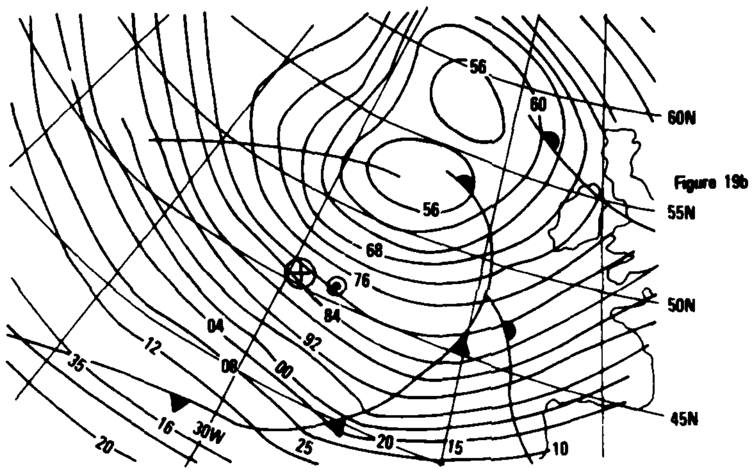


Figure 19b - Surface Weather Map for 12 December 1978; 0001 GMT

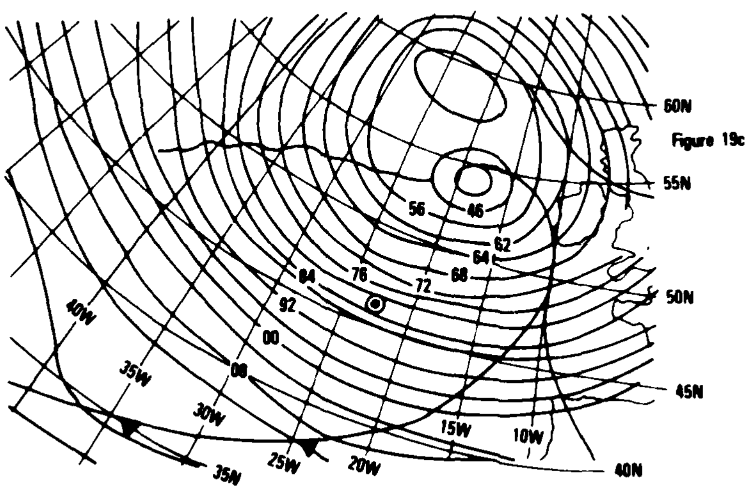


Figure 19c - Surface Weather Map for 12 December 1978; 0600 GMT

Figure 19 - Surface Weather Maps for Vicinity of MÜNCHEN Near Time of Distress Call at 0310 GMT on 12 December 1978

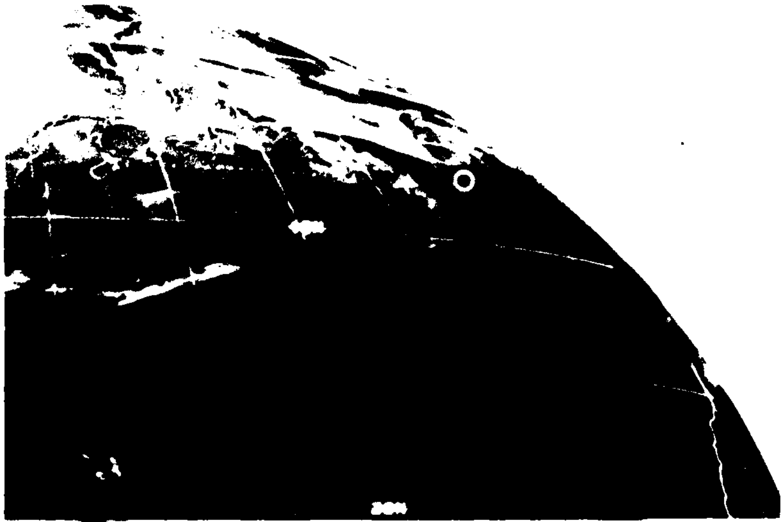


Figure 20a - Comma Cloud Forming and Approaching Casualty Site: 12 December 1978; 0001 GMT

⊙ **CASUALTY SITE**

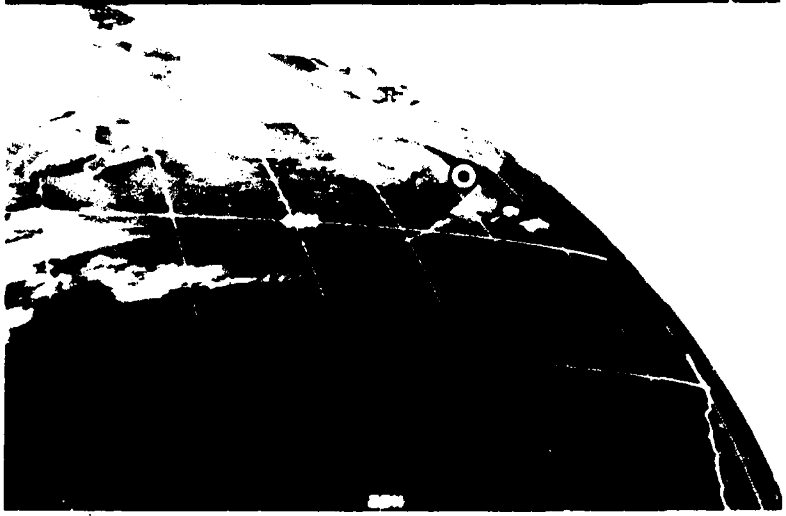


Figure 20b - Comma Cloud Passing Over Casualty Site: 12 December 1978; 0600 GMT

Figure 20c - Comma Cloud Beyond Casualty Site: 12 December 1978; 1200 GMT

Figure 20 - Satellite View of Cloud Formation in Vicinity of MUNCHEN Near Time of Distress Call at 0310 GMT on 12 December 1978

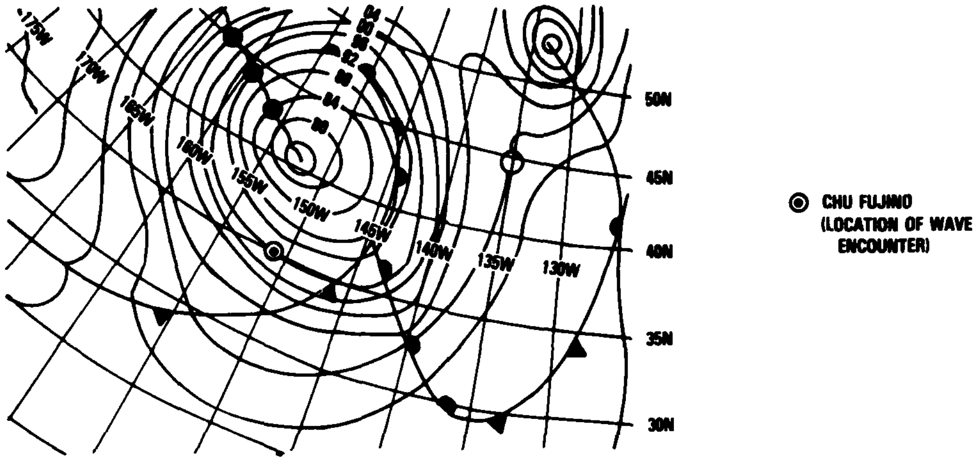


Figure 21a - Surface Weather Map for 28 December 1979; 1800 GMT

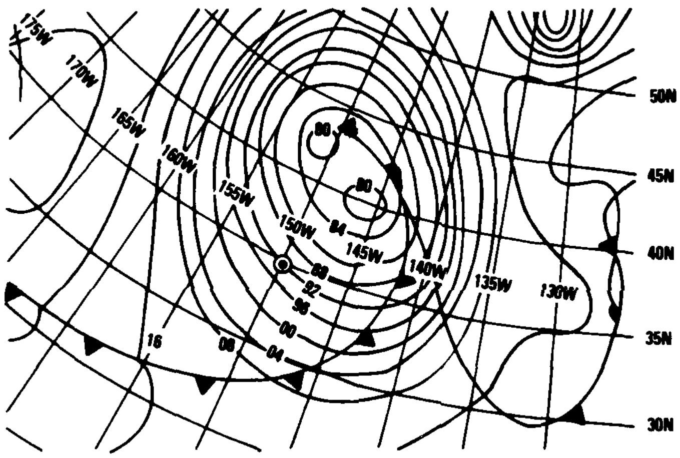


Figure 21b - Surface Weather Map for 29 December 1979; 0001 GMT

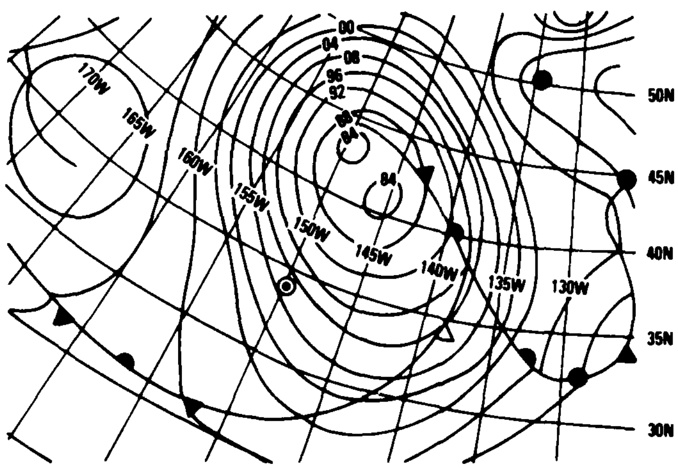
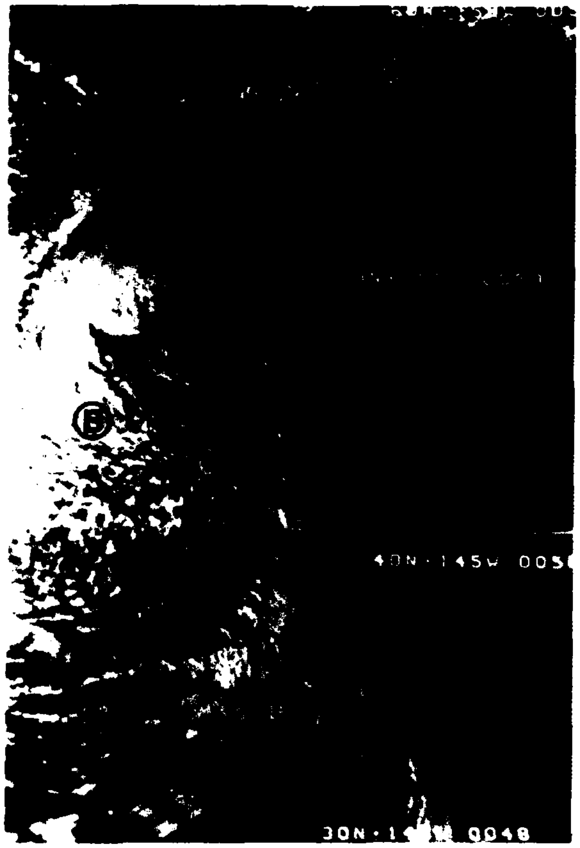


Figure 21c - Surface Weather Map for 29 December 1979; 0600 GMT

Figure 21 - Surface Weather Maps for Vicinity of CHU FUJINO Near Time of "Rogue" Wave Encounter at 0140 GMT on 29 December 1979



NOTES:
Ⓐ SHIP'S POSITION AT 0052 GMT ON 28TH
Ⓑ ESTIMATE OF SHIP'S LOCATION RELATIVE TO CLOUD PATTERN AT 0140 GMT ON 29TH.
FROM FIGURE 57 OF REFERENCE 33.

Figure 22a - Head of Comma Cloud Approaching Site of Rogue Wave Encounter (Photo taken 0052 GMT on 28 December 1979)

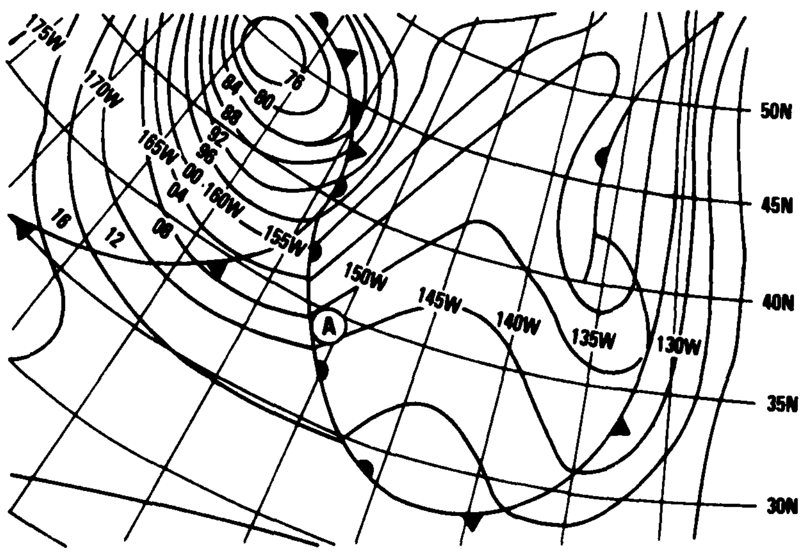


Figure 22b - Surface Weather Map for 28 December 1979; 0001 GMT

Figure 22 - Approach of Head of Comma Cloud to Site of "Rogue" Wave Encounter by CHU FUJINO at 0140 GMT on 29 December 1979

storm and well behind an occluded cold front. He further notes[9] that the large (10 meter diameter) discus buoys have withstood much higher significant wave heights including those resulting from hurricanes in the Gulf of Mexico without capsizing. He believes that the unique wave conditions associated with the passage of the TROF are a critical factor.

The TROFs associated with the capsizings appear to be typically associated with the head of the comma-shaped cloud pattern during a later phase of the storm when the original TROF associated with transient intensification has moved eastward. The tendency for the critical wave condition to be associated with a later phase of the storm development is believed reflected in the isopleth patterns of rapid storm ("bomb") development presented by Sanders and Gyakum.[30] Figure 24 locates NOAA, data buoy capsizings, and the episodic wave encounters of the MÜNCHEN (presumed) and CHU FUJINO with respect to the isopleth contours. These can be seen to lie near the eastern edge of the regions most often associated with "bomb" development as might be expected if they were associated with latter (or subsequent) phases of storm development.

(3) U.S. NAVY FRIGATE Wave Damage Incident

Although there are certain aspects of the wave encountered by the NAVY FRIGATE which are similar to those encountered by the M.V. MUNCHEN and M.V. CHU FUJINO (see 5.2.2), the general synoptic weather pattern was considerably different. The surface weather map of Figure 25 shows a warm front passing the vicinity of the ship at the time of the incident. No wind vectors exceeding 35 knots are shown, which is consistent with the generally low sea state (10-12 foot waves) observed at the time by the ship. The intruding episodic wave packet from the south southeast implies stronger winds blowing from that direction south and east of the ship's location contrary to the implications to the surface weather map. Wind vector data furnished by the Seattle Oceans Services Unit of NOAA[34] for a time six hours before the incident* shows surface winds of 35 knots from the southeast off the lower Oregon coast which are substantially misaligned to the isobars of Figure 25. The extent of this particular wind field in relationship to the ship's location can not be determined from the available information. As in the case of the MÜNCHEN and CHU FUJINO, it is clear that the surface weather map, due to a lack of closely spaced observations from ships at sea, is inadequate for describing the wind field in the region of the episodic wave event.

In this case, weather satellite views of the associated cloud pattern show no evidence of a TROF interacting with a surface low since there was no major storm activity involved in the immediate area. The incident is believed to illustrate that abruptly angled wind fields can exist under conditions much less drastic than those associated with the MÜNCHEN and CHU FUJINO, and that rogue waves of smaller proportions can also be encountered.

6.2 Effects of Large Non-Gaussian and Episodic Waves on Ships

The encounters with large waves described in Section 5 are also of interest from a structural design point of view. Because of the limited number of incidents

*Observations for a time closer to 0600 GMT on 13 February 1982 are not available.

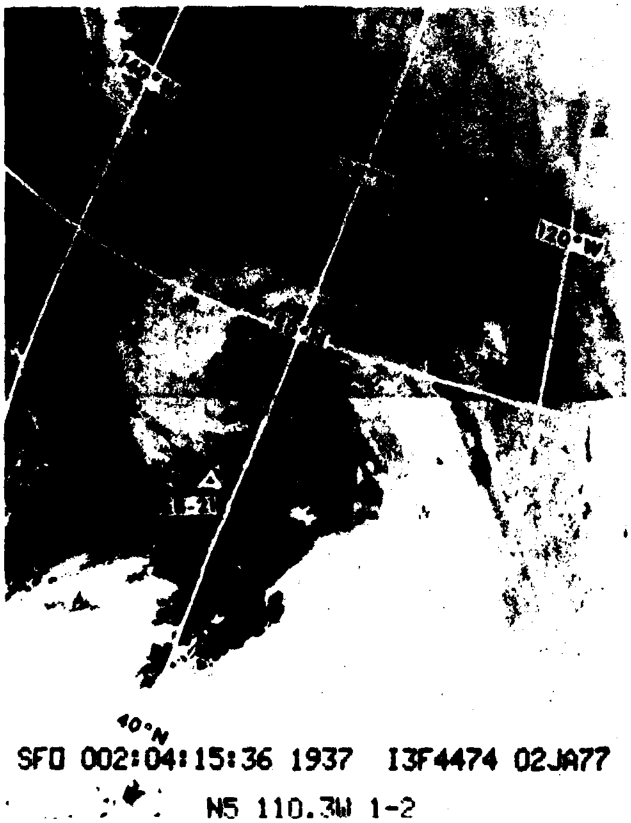
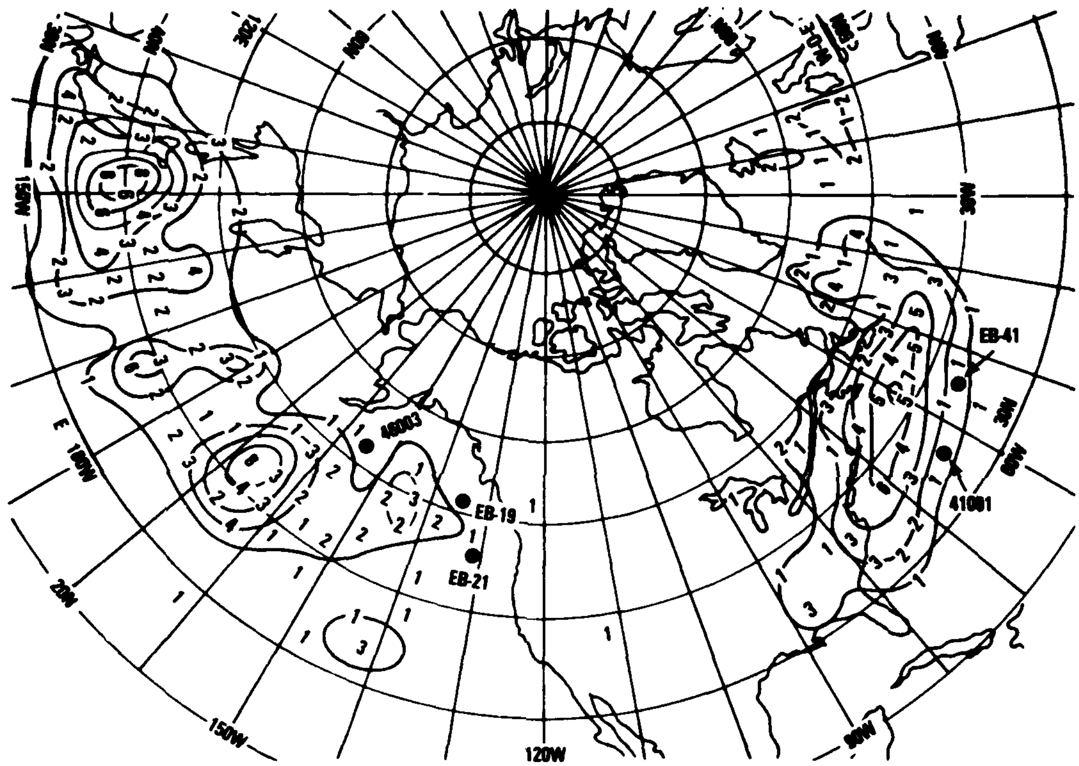


Figure 23a - NOAA-5 Infrared Satellite Image at 0415 Hours on 2 January 1977

Figure 23b - NOAA-5 Visible Satellite Image at 1815 Hours on 2 January 1977

Note:
1. Last report from buoy at 1200 GMT on 2 January 1977.
2. From Figures 4 and 6 of Reference 10.

Figure 23 - Cloud Pattern Associated with Capsizing of NOAA Data Buoy in North Pacific Ocean



Note: Isopleths define distribution of "Bomb" events during three cold seasons. From Figure 3 of Sanders and Gyakum.30

Figure 24 - Relationship of NOAA Data Buoy Capsizings to Regions of Development of Intense Winter Storms

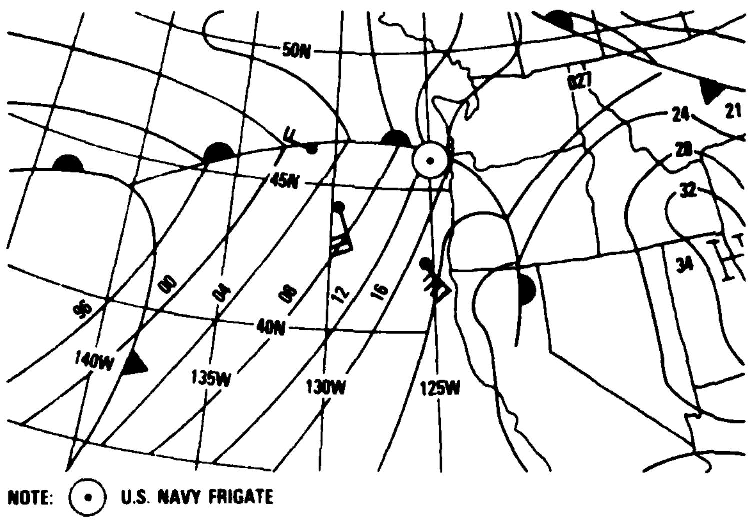


Figure 25 - Surface Weather Map for Vicinity of U.S. NAVY FRIGATE at Time of "Rogue" Wave Encounter at 0518 GMT on 13 February 1982

which have been reviewed, the damages are significant primarily from the point of view of evident relationships between wave characteristics and the particular damage which they caused as opposed to general damage trends per se.

6.2.1 Steep, Elevated Waves

The CHESTER A. POLING casualty is believed to demonstrate that large waves of this type can result in wave induced bending moments of a substantial nature in the case of ships of relatively short length. The time-series character of the waves as shown in Figure 11 and as implied by Figures 12 and 13 suggests that the resulting sagging moments will be influenced substantially by the heaving motion of the bow of the ship as it encounters such a wave especially in the case of ships with considerable fullness forward. The high incidence of "bomb" development along the U.S. east coast shown in Figure 24 identifies an area of concern for coastal vessels which might otherwise be expected to avoid such extreme wave conditions.

The SEA-LAND MARKET and U.S.S. SHREVEPORT illustrate that the combined size and steepness of these waves can result in significant damage forward when the ship in question is long and does not rise rapidly as the wave is encountered. Obviously hull form forward and over-all ship length are important characteristics in determining whether or not the existence of such waves requires special attention in the structural design of the foreship area.

The F/V FAIR WIND casualty raises questions which are primarily of a non-structural nature. Vessel stability and especially optimum handling tactics in large, breaking waves such as shown in Figure 12 appear to be of primary concern.

Although no casualty case has been examined in this study comparable to those discussed by Szostak[35] relative to large tankers, it is believed reasonable to conclude that large, steep waves can lead to substantial local hydrostatic loadings on large, fully ladden tankers which are swept by such waves. The short wave length and elevated nature of the waves implies that such ships will have a limited tendency to rise upon encountering them and that unusual depths of green water on deck can occur. The hydrostatic crushing loads on web frames under these circumstances are likely to be important. Thus the recommendation by Szostak[35] that water depths on deck be related to actual wave characteristics as opposed to "design wave" heights is believed well taken.

6.2.2 Episodic Waves

The large grouped waves encountered by the S.S. SEA-LAND McLEAN and U.S.S. INDEPENDENCE illustrate that the time-series character and large size of these waves can result in substantial hull girder bending stresses in long ships, especially when the hull form is such that heavy slamming can occur when the second wave in the group is encountered. The lack of identifiable time-series height measurements for such waves is a serious deterrent to a more deterministic understanding of their effect on long ships (and additionally from the point of view of recreating such waves at model scale in test tanks).

Episodic wave packets of the "three sister" variety appear to be of immediate interest from a cargo tie-down point of view considering the large roll angles which they are likely to induce. Again the lack of indentifiable time-series wave height data is unfortunate.

The "rogue" wave encounters by the M.V. CHU FUJINO and U.S. NAVY FRIGATE and presumably by the M.V. MÜNCHEN are doubtless the most disconcerting incidents examined here with respect to critical wave proportions and attendant structural damage. Such wave events appear to be sufficiently infrequent that the prospects of obtaining applicable time-series wave height data are poor. Other possibilities may have to be considered in the instance.

From the point of view of improving ship structure to withstand "rogue" wave loadings, the prospects are somewhat better. The damages associated with the CHU FUJINO and the U.S. NAVY FRIGATE involved the effects of wave impact loadings on local structure primarily. Damage which would appear to require major strengthening of the hull girder was not in evidence. By inference the same may be said of the MÜNCHEN. Since "rogue" wave encounters are very infrequent, repairable damage is suggested here as being entirely acceptable so that the primary concern in structural design is the maintenance of watertight integrity.

The CHU FUJINO damages are instructive in this regard:

(a) "Bolted engine room access plating on deck forward of bridge buckled and torn loose, allowing water entry to engine room." The ship was without power entirely for about an hour following the incident.

(b) "Wing/ballast tank vents damaged, baffle plates washed away, floats fell out, and wing tanks flooded." "Foc'sle storeroom; fwd pumproom; No. 1 and No. 2 double bottoms, port and starboard; forepeak tank-all completely flooded." Subsequent cumulative flooding nearly caused the ship to founder.

(c) "Starboard bridge windows smashed in. Starboard lifeboat washed away and davits flattened to deck. Two starboard aft liferafts and foredeck liferaft washed away." The inferred loss of primary radio transmission capability in the MUNCHEN casualty and the loss of its starboard lifeboat suggest that similar and perhaps more severe window and other deckhouse damages may have been experienced in that instance. (It might also be noted in passing that a local loss of watertight integrity under less trying circumstances was noted by the S.S. LASH TURKYIE in Case 23 of Table A-1 of Appendix A). Bridge window failures were also experienced by the NAVY FRIGATE even though the rogue wave encountered was substantially smaller than that encountered by the CHU FUJINO.

The suggestion here is that loss of watertight integrity due to excessive deformation or structural collapse due to any wave encounter should be considered as prima facie evidence of a need for improving the ultimate strength of the component involved provided improper fabrication, securing, sealing, etc. was not in evidence. "Hardening" or elimination, or relocation of components in such empirical fashion could be of considerable importance in assuring that loadings associated with "rogue" wave encounters will not jeopardize the watertight integrity of a ship. While a more rational understanding of such wave loadings is desired, it is believed that structural improvements need not wait for this to be achieved.

7.0 CONCLUSIONS

(a) Despite certain semantic and perceptional problems, the identification of large, non-Gaussian and episodic waves in Hurricane Camille wave data by half-cycle analysis techniques has provided a basis for discussing damaging storm waves during interviews with ship's masters and officers of considerable at-sea experience. The results of these interviews confirm earlier indications of the potentially damaging nature of such waves. The additional characterization of these waves with respect to long-crestedness and alignment or misalignment with the dominant wave pattern of a storm-driven seaway has been of vital importance in establishing an initial characterization (Table 2).

(b) Recent developments in the mechanics of non-linear waves and in the study of rapidly developing winter storms provide important clues regarding the synoptic weather conditions associated with the development of large, non-Gaussian waves. In this regard, the type of winter storm characterized by Sanders and Gyakum[30] as "the bomb" appears to be of considerable importance.

(c) Wave impacts are a major cause of heavy weather damage as compared to overall hull girder loadings. Thus research associated with ship structural loadings in extreme seas must also deal effectively with this class of problem to be of significant value to practicing naval architects.

(d) Maintenance of watertight integrity appears to be the primary requirement (chiefly involving doors, hatches, ventilators, windows, etc.) when a ship encounters a "rogue" wave. It follows that significant losses of component watertight integrity in heavy weather of any type should be examined critically with respect to the need for structural or other modifications in order to assure safety under the extreme conditions associated with "rogue" wave encounters.

8.0 RECOMMENDED PROGRAM OF RESEARCH

It has not been possible within the scope of the present study to pursue in a substantive manner the many initiatives which have evolved during its conduct. As a result, the program of research which is recommended here is both diverse and, in some cases, tenuously charted because of limited progress to date in certain areas. Nevertheless, if a rational understanding of ship structural loadings in extreme seas and of associated strength standards is to be realized, the recommended program can not be arbitrarily limited to familiar areas of research or to tasks whose approach is necessarily clear and well defined.

8.1 Continuing Survey of Ship Damages and Extreme Wave Encounters

The interviews with ship's masters and officers conducted in this study should be restructured and expanded to permit interviews with ship's personnel at the earliest opportunity following major heavy weather damage incidents rather than long after the fact. Moreover, certain basic information should be gathered in documented form. There is at the present time a network of cooperating ships which periodically furnish local wind, wave, and meterological information to the U.S. National Weather Service. If this network could also furnish information regarding extreme wave encounters and related ship damages on those infrequent occassions when there is a significant incident, there would exist considerable potential for adding to the information gained from the interviews summarized here as well as adding to the type of information obtained regarding the CHU FUJINO and the U.S. NAVY FRIGATE wave damage incidents.* A condensed version of the present report could serve as an introduction to such an information gathering program.

Consideration should also be given generally to gathering information regarding structural components which fail to maintain water tight integrity under wave impact loadings particularly those which, under extreme wave conditions, could disrupt radio communication, cause loss of control or ship powering, or cause serious loss of ship stability or buoyancy.

8.2 Wave and Wind Data Acquisition and Analysis

The information obtained from Hurricane Camille wave and wind data regarding the existence and time-series character of large, non-Gaussian and episodic waves as well as concurrent wind data has been of vital importance in the present study. Much more time-series wind and wave data must be obtained and analyzed for synoptic weather conditions which have been found to be of interest as the result of this and other studies if additional progress is to be made regarding the existence and characteristics of extreme waves.

One of the logical sources of the desired time-series data are those ocean weather ships still in use in the North Atlantic Ocean as well as deep-water offshore platforms or drilling rigs incorporating wave and wind measuring and recording systems. Unfortunately, the large ocean data buoys currently deployed off the U.S. coasts are not capable of providing time-series wave and wind data at this time. Difficulties also exist regarding the proprietary aspects of wind and wave data in the case of offshore platforms and drilling rigs. Despite these problems there is reason to believe that important time-series data can be obtained.

The acquisition and analysis of meso-scale data for surface wind fields resulting from the interaction of TROF-like disturbances with both developing and mature surface lows is of considerable importance with respect to understanding the origin of episodic wave packets. The enormous area covered by even a small TROF-like disturbance presents a major deterrent to progress in this case although satellite-borne sensors may prove to be helpful in providing at least indirect evidence of the desired surface wind field information.

8.3 Technology Development

(a) The Identification of Non-Gaussian Events in Quasi-Stationary Time-Series Data of Arbitrary Spectral Form. As discussed in Section 2, a capability exists at present for identifying the existence of non-Gaussian events in a band-limited, white noise process. It is important that this capability be extended to apply to stochastic processes of arbitrary spectral form for a more exact identification of non-Gaussian events in wave or other time-series data. The desired capability is considered to require processing of the time-series data directly into half-cycle matrix (HACYM) format and, additionally determining the variance spectrum for the same time-series data. By summing electrically generated Gaussian random variables

*The most recent version of the data table entitled "Ship's Weather Observations" provided to cooperating ships in fact requests much of the desired information under "Freak Wave Report."

corresponding to the discrete energy/frequency constituents of the spectrum,[36] a new Gaussian time-series can be generated and processed into HACYM format for direct comparison with the HACYM data obtained from the original time-series. The purpose of the comparison is to identify non-Gaussian events in the original data for further study as to their particular time-series characteristics and origin from a cause and effect point of view.

This capability is also of importance in the analysis of random wave data from test tanks to determine whether or not the seaway being modeled in the frequency domain is Gaussian or not.

(b) Generation of Waves of Specified Time-Domain Character in Test Tanks. Because of the existence of large non-Gaussian waves in nature and their potentially damaging effects on ships, it is recommended that consideration be given to generating model-scale versions of such waves in linear and maneuvering tanks. The time-series wave data of Figure 11 provides a starting point for modelling purposes. Tests of a model of the SL-7 container ships in such waves is likely to be instructive because the tendency of this class of ship toward foredeck and deck house damage has not been revealed by previous model tests in regular and random seas, the latter presumably being essentially Gaussian in character. (See Section 2 and Figure 5).

(c) Propagation Characteristics of Imperfect Soliton Wave Packets. The research of Yuen and Lake[25] reviewed in Section 6 which relates to the stability of soliton wave packets having imperfect height envelopes, should be carried forward both analytically and experimentally to consider the more general case of imperfect wave periods and heights. The instability characteristics of such packets is also apt to be of considerable importance in explaining the origin of "rogue" waves.

(d) Wind Generation of Imperfect Soliton Wave Packets. As mentioned in Section 6, no explanation has been offered regarding the apparent ability of storm winds to generate imperfect soliton wave packets. Recent investigations by Mollo-Christensen and Ramamonjiarisoa,[37] however, appear to be moving in this direction although they have not been structured to deal specifically with this question. The technique which they employ of injecting mechanically generated waves into the wind field of their test flume would appear to overcome to some degree the markedly overdriven wind-wave field characteristic of such facilities (see Section 6). It is recommended that the methods employed in their work be examined to determine the feasibility of studying the generation of waves in wind-wave fields which are overdriven by an order of magnitude less than in previous experiments.

(e) Ultimate Strength Analysis Methods. The acceptability of damage to structural components, in the absence of significant loss of water tight integrity, as suggested in the discussion of "rogue" wave damage, in Section 6, necessarily leads to a recommendation for developing appropriate structural analysis methods. In the case of bridge windows, special design features are likely to be required as well as dynamic structural analysis methods.

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REFERENCES

1. Buckley, W.H. and A.B. Stavovy, "Progress in the Development of Structural Load Criteria for Extreme Waves," SSC/SNAME Extreme Loads Response Symposium, 19-20 October 1981, SY-14, pp 75-88.

2. Buckley, W.H., "The Application of Half-Cycle Counting Techniques to the Analysis of Ocean Wave Data," Proceedings of the 19th American Towing Tank Conference, Volume 1, 9-11 July 1980, pp 429-466.

3. Yang, J.N., "Statistics of Random Loading Relevant to Fatigue," ASCE Journal of the Engineering Mechanics Division, June 1974, pp 469-475.

4. Andrews, J.N., "Analysis of an Idealized Narrow-Band Random Process in Half-Cycle Matrix Format," (report in preparation).

5. Cartwright, D.E. and M.S. Longuet-Higgins, "The Statistical Distribution of the Maxima of a Random Function," Proceedings of the Royal Society of London, Series A Mathematical and Physical Sciences, Vol. 237, 20 November 1956, pp 212-232.

6. Earle, M.D., "Extreme Wave Conditions During Hurricane Camille," Journal of Geophysical Research, Vol. 80, No. 3, 20 January 1975, pp 377-379.

7. Pierson, W.J. Jr., G. Neumann, R.W. James, "Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics," H.O. Pub. No. 603, 1955, Table 2.1.

8. Longuet-Higgins, M.S., "On the Statistical Distribution of the Heights of Sea Waves," Journal of Marine Research, Volume XI, No. 3, 1952, pp 245-266.

9. Hamilton, G.D. "Buoy Capsizing Wave Conditions," Mariners Weather Log, Volume 24, Number 3, May-June 1980, pp 165-173.

10. Mallory, J.K., "Abnormal Waves on the South East Coast of Africa," Institute of Oceanography, University of Cape Town, Occassional Report 787/1, August 1977.

11. Schumann, E.H., "Changes in Energy of Surface Gravity Waves in the Agulhas Current," Deep-Sea Research, Volume 23, 1976, pp 509-518.

12. Schumann, E.H., "High Waves in the Agulhas Current," Mariners Weather Log, Volume 20, Number 1, 1976, pp 1-3.

13. Hogben, N. et al., "Report of Committee I.1 Environmental Conditions: 3 Special Risk Conditions," Proceedings of the Seventh International Ship Structures Congress, Volume 1, August 1979, pp I.1-72 to 84.

14. Hawkins, S., G.H. Levine, R. Taggart, "A Limited Survey of Ship Structural Damage," Ship Structure Committee Report SSC-220, 1971.

15. Quayle, R.G., "Weather and Maritime Casualty Statistics," Mariners Weather Log, Volume 20, Number 2, March 1976, pp 74-80.

16. "Marine Accident Report: Sinking of the M/V CHESTER A. POLING Near Cape Ann, Massachusetts, 10 January 1977," National Transportation Safety Board Report Number: NTSB-MAR-78-7, 14 September 1978.

17. Proceedings of Investigation to inquire into the circumstances connected with the storm damage incurred by U.S.S. SHREVEPORT (LPD 12), U.S.S. INCHON (LPH 12), and U.S.S. FAIRFAX COUNTY (LST 1193), which occurred on 1 and 2 February 1976, Dept. of the Navy, Office of the Judge Advocate General, 12 March 1976.

18. "Rough Log, North Atlantic Weather: October and November 1980," Mariners Weather Log, Volume 25, Number 1, January-February 1981, pp 59.

19. United States Coast Guard Investigation: F/V FAIR WIND-Investigation into the Sinking with Subsequent Disappearance and Presumed Loss of Life on 22 November 1980, 16 March 1982.

20. Official Transcript of Proceedings of a Formal Investigation: Case No. 16732/6931 in the Matter of: The Circumstances Surrounding the Casualty of the Fishing Vessel FAIR WIND Official Number 546663 on or about 22 November 1980, in the North Atlantic Ocean off Cape Cod Massachusetts, 4 December 1980.

21. Proceedings of Investigation to Inquire into the Circumstances Connected with the Damage which Occurred to Units of Commander Task Group 21.2 on or about 7 April 1977, Dept. of the Navy, Office of the Judge Advocate General, 28 April 1977.

22. Telex report of interview with Master of M/V CHU FUJINO prepared by Adm. Merlin H. Staring (U.S.N. Ret.).

23. Marine Court Bremerhaven, Minutes of Hearing: In the Case of the Sea Court Inquiring into the Loss of the Barge-Carrying Vessel MÜNCHEN in the North Atlantic on 13 December 1978, (free translation) 12 June 1980.

24. Results of telephone conversation with U.S. Navy personnel conducting damage survey of U.S. NAVY FRIGATE, 19 February 1982.

25. Yuen, H.C. and B.M. Lake, "Nonlinear Wave Concepts Applied to Deep-Water Waves," in Solitons in Action, Academic Press, 1978, pp 89-126.

26. Lake, B.M. and H.C. Yuen, "A New Model for Nonlinear Wind Waves, Part 1, Physical Model and Experimental Evidence," Journal of Fluid Mechanics, Volume 88, Part 1, pp 33-62, 1978.

27. Benjamin, T.B. and J.E. Feir, "The Disintegration of Wave Trains in Deep Water, Part 1, Theory," Journal of Fluid Mechanics, Volume 27, 1967, pp 417-430.

28. Phillips, O.M., "Wave Interactions - The Evolution of an Idea," Journal of Fluid Mechanics, Volume 106, 1981, pp 215-227.

29. Yuen, H.C. and B.M. Lake, "Nonlinear Deep Water Waves: Theory and Experiment," Physics of Fluids, Volume 18, No. 8, August 1975, pp 956-960.

30. Sanders, F. and J.R. Gyakum, "Synoptic-Dynamic Climatology of the 'Bomb'," Monthly Weather Review, Volume 108, October 1980, pp 1589-1606.

31. Reed, R.J., "Cyclogenesis in Polar Air Streams," Monthly Weather Review, Volume 107, January 1979, pp 38-52.

32. Mariners Weather Log, Volume 23, No. 3, May 1979, p 201.

33. Mariners Weather Log, Volume 24, No. 2, March 1980, p 156.

34. Letter from R.W. Anderson, Chief, Seattle Ocean Services Unit, 10 March 1981.

35. Szostak, D.J., "Yesterday's Technology-Today's Ships-Some Tanker Experience," SSC/SNAME Ship Structure Symposium '75, SY-5 1976, pp G-1 to G-13.

36. Yang, J.N., "On the Normality and Accuracy of Simulated Random Processes," Journal of Sound and Vibration, Volume 26, No. 3, 1973, pp. 417-428.

37. Mollo-Christensen, E. and A. Ramamonjiarisoa, "Subharmonic Transitions and Group Formation in a Wind Wave Field," to be published in Journal of Geophysical Research.

APPENDIX A

A LIMITED SURVEY OF U.S. COAST GUARD HEAVY WEATHER DAMAGE INFORMATION

The origin of the data base and the criteria used for selection of the heavy weather damage cases summarized in Table A-1 are discussed in Section 3 together with a brief interpretive summary of the information. The following additional comments are offered regarding the information contained in Table A-1.

The damage cases have been ordered by "year built" so that trends associated with newer vs. older ship design and construction would be more evident where they happen to exist. It is evident from this ordering, for example, that ships of more recent design are longer and of higher displacement than the older ships. Eight of the 38 ships reviewed in the table were built during or immediately following World War II and 5 of those were apparently modified to carry containers. The casualty dates it will be noted, bear no particular relationship to the age of the ship in question.

The entries regarding ship particulars are those appearing on the CG-2692 form except that some lengths and tonnages have been rounded off to the nearest foot or ton. The entries regarding ship length can be either registered length or length over-all and where one or the other was specified it is so noted in the table. Forward and aft drafts were included in the table in the event slamming was a significant source of damage (which in general it was not).

The description of casualty information contains quotes where the information was taken directly from the form. In some cases damage information is also included in the remarks column. The time of casualty information in the CG-2692 form is apparently intended to refer to local time with the required correction to correspond to GMT noted. Where GMT time was specified in the form, it is noted in the table.

The estimates of height of sea and height of swell in the form are apparently somewhat ambiguous. Where the sea and swell approached from different directions a clear distinction appears to exist. However, where they were evidently aligned it was not uncommon to find the same wave heights stipulated for each, or for only one or the other to be given. For such cases little guidance can be offered except to suggest that it would probably be unwise to add sea and swell wave heights together to estimate maximum wave height.

Sea and air temperature have been included in the table since air temperatures substantially less than sea temperatures are frequently indicative of gustiness associated with unstable and highly connective air masses.

Finally, in searching the computer listing originally furnished by the Coast Guard an effort was made to identify casualty cases associated with SL-7 class container ships. This was done because of the large number of research investigations sponsored by the Ship Structure Committee in connection with these ships and the resulting availability of design, test, and service information. When it was noted that there was an apparent class problem with respect to foredeck and deckhouse damage, an effort was also made to identify casualties associated with LASH ships because they are also relatively long ships with a deckhouse located well forward on the hull. Since the computer listing was not catalogued by class of ship, there is no certainty, however, that all damage cases involving these two classes of ships were located within the data base.

TABLE A-1 - A LIMITED SURVEY OF U.S. COAST GUARD HEAVY-WEATHER DAMAGE INFORMATION

REFERENCE NUMBER	COAST GUARD CASE NUMBER	VESSEL TYPE / VESSEL NAME	YEAR BUILT / OFFICIAL NUMBER	LENGTH / DRAFT FWD/AFT	GROSS TONNAGE / TYPE CARGO	DESCRIPTION OF CASUALTY
1	82760	Tanker (Containership)	1942	523 Ft 06 In LOA	9,315 Tons	Vessel on course 345 at full sea speed. Moderate to heavy seas one point forward of port beam. Occasional seas over main deck. 47 containers lost or destroyed. Containers port, aft and starboard, forward were lost. Yawing of vessel believed to have overstressed corner posts of several containers.
		S.S. CARBIDE SEADRIFT	241851	28 Ft/31 Ft	Containers and Tanks	
2	51676	Container	1942	627 Ft 05 In LOA	16,395 Tons	Rudder failure. ". . .the vessel took a particularly deep pitch, rose to the crest of the swell, and then 'dropped' onto the next succeeding swell 'pounding' very heavily, and 'panting' considerably."
		S.S. ELIZABETH PORT	242557	20 Ft/22 Ft	General	
3	51901	Container	1943	494 Ft 02 In	11,476 Tons	"While proceeding under hove to conditions (40-45 RPM) a series of mountainous waves driven before squall of severe intensity struck vessel doing various degrees of damage to three containers."
		S.S. ANCHORAGE	243850	27 Ft/29 Ft	Containerized General	
4	40716	Freighter	1944	455 Ft 03 In	7,639 Tons	"The port forecastle bulwark was carried away in a gale on the night of June 22, 1973." ". . .cause of casualty was the taking of an unusually large swell over the port bow during heavy weather."
		S.S. LONGVIEW VICTORY	247077	26 Ft/29 Ft	Ammunition (Military)	
5	83370	Freighter/ Converted T-2	1944	602 Ft 05 In	15,995 Tons	"The vessel damage consisted of two lost vents to upper wing ballast tanks and minor shell plating cracks in way of the engine room spaces. The lost vents allowed salt water to reach and spoil 4000 tons of wheat."
		S.S. MERRIMAC	245673	33 Ft/36 Ft	Wheat	
6	51280	Container - Freight	1945	497.2 Feet	11,389 Tons	"On the ship's bow about 40 feet off the port side bulwark between web frames 6-24 was entirely torn away and most of it lost overboard. The main deck was holed in three places at its extreme port side edge. . . .The front ends of two containers were stove in."
		S.S. CHARLESTON	248095	23 Ft/27 Ft	General Cargo in Containers	

Note:
Table
Continued on
Next Page

TABLE A-1 (Continued)

Reference Number	Date / Time (Zone) / Location	Body of Water / Port Of Departure / Bound To	Sea Condition / Height Of Sea / Direction Of Sea	Weather Condition / Height Of Swell / Direction Of Swell	Wind Direction / Wind Velocity / Gusty	Visibility / Sea Temperature / Air Temperature	Repair Cost / Cargo Loss / Ship Heading	REMARKS
1	26 Jan 1978	Atlantic Ocean	Rough	Overcast	Westerly	10 Miles +	$100 K	Sudden Drop And Recovery Of Barometric Pressure (4 to 5 mb) At Time of Incident. Cause Of Sharp Yawing Of Vessel Unexplained.
	2249 GMT	Guayanilla, P. Rico	10-15 FT	15-20 FT	25-30 KN	66°F	$800 K	
	33-34N, 73-07W	New York, N.Y.	Westerly	Westerly	No	52°F	345° Gyro	
2	25 Dec 1974	North Atlantic	Very Rough SW Sea Heavy SW Swell	Overcast, Squalls	SW	Variable 2-5 Miles	$20 K	Wave Sequence And Wind Strength Similar To That When S.S. SEALAND McLEAN Experienced Extreme Hull Girder Bending Stresses
	1500 GMT	Cadiz, Spain	15+ FT	20+ FT	70-90 KN	73°F	0	
	37.7N, 63.4W	New York, N.Y.	SW	SW & WNW Confused	Yes	60°F	?	
3	24 Nov 1973	Atlantic Ocean	Exceptionally Rough	Overcast	NW	Good, 7 Miles	$0 K	Containers Lifted By Water On Deck At Hatches 6 And 7
	1136 (+4)	Cadiz, Spain	30-40 FT	No Defined Swell	60-70 KN	72°F	$100 K	
	37-20N, 55-20W	Elizabeth, N.J.	NW	–	Yes	65°F	?	
4	22 June 1973	Pacific Ocean	Very High	Overcast, Rain	SW	3 Miles	$25 K	
	1800-2400 (+9)	San Francisco, Calif.	20 FT	25 FT	50 KN	60°F	$0 K	
	39-35N, 138-05W	Okinawa, Japan	SW & Confused	SW	No	60°F	?	
5	23 Feb 1978	Atlantic Ocean	Very Rough	Overcast, Rain	Westerly	Fair, 5 Miles	$85 K	
	0400 (+4)	Norfolk, Virginia	35 FT	Unknown	60 KN	68°F	$400 K	
	33-25N, 55-08W	Alexandria, Egypt	Westerly	Unknown	Yes	61°F	?	
6	2 Jan 1975	Atlantic Ocean	Very Rough	Clear	N x E	15 Miles	$10 K	Ship Slowed Incrementally Beginning At 0518 To 0745 Hours. Heavy Sea Broke Over Bow At 0745
	0745 (+5)	Houston, Texas	12 FT	15 FT	34-40 KN	78°F	$0 K	
	32-06N, 77-48W	Elizabeth, N.J.	Northerly	Northerly	Yes	?	053° Gyro	

TABLE A-1 (Continued)

REFERENCE NUMBER	COAST GUARD CASE NUMBER	VESSEL TYPE / VESSEL NAME	YEAR BUILT / OFFICIAL NUMBER	LENGTH / DRAFT FWD/AFT	GROSS TONNAGE / TYPE CARGO	DESCRIPTION OF CASUALTY
7	82815	Freighter	1945	551.9 Feet	15,147 Tons	"Lost port gangway, bridle and wires. Port catwalks alongside port hatch coamings damaged." (Damage list given). "Heavy seas and swells washing over main decks and hatches."
		S.S. OVERSEAS TRAVELER	289436	33 Ft/33 Ft	Coal	
8	21065	?	1946	468 Ft 05 In	?	"At 1315 hours 16 Dec C/C from 240° gyro to 295° gyro to ease heavy rolling due to very high N'ly sea and short heavy 35 foot swell. At 1330 C/C 305° gyro, 1435 vessel rolled 38 degrees in short heavy 35 foot N'ly swell, C/C 020° gyro and reduced speed to (50)RPM 1505 reduced speed to 40 RPMs. At 1512 vans went over port side #5 hatch."
		S.S. PRESIDENT MADISON	249683	?/27 Ft	Deck Containers	
9	21016	Freighter	1953	563.07 Feet (?)	9,069 Tons	"While hove to N'ly storm in Lat. 27-17 N Long. 171-40 W Vessel suddenly rolled 40° port to starboard causing deck load to shift with loss of 6 vans overboard and damage to 22 other vans stored on deck."
		S S PRESIDENT JACKSON	266060	29 Ft/30 Ft	General	
10	40744	Tanker	1959	712.1 Feet	24,493 Tons	"1622 boarded by heavy sea over port bow. 1624 struck by another heavy sea on portside. Reduced speed to 80 RPM heavy seas and cross swells - vessel steering poorly. 0800 vessel had slight port list. Inspection showed approximately 4 feet of water in #6 port ballast wing tank. Damage to deck piping."
		S S THETIS	279627	37 Ft/36 Ft	Arabian Crude Oil	
11	41428	Container	1964	668 Ft 7¾ In	16,542 Tons	"Vessel proceeding at reduced speed in moderately rough WSW swell in moderate SW sea. Took heavy sea on starboard side forward of midship house; sea broke out port hole in Chief Mate's room, also one window in stb'd passenger lounge; sustained heavy water damage in both areas and passageways and passenger rooms."
		S.S. OREGON MAIL	296779	28 Ft/30 Ft	Containers	
12	42069	Drilling Barge	1966	220 Feet	2,778 Tons	"Broken moorings, damage to vent piping. Loss of one life raft. Damage to keel cool system due to adverse weather conditions."
		BLUEWATER 3	503-347	39 Ft/39 Ft	Drill Equipment	

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TABLE A-1 (Continued)

Reference Number	Date	Body of Water	Sea Condition	Weather Condition	Wind Direction	Visibility	Repair Cost	REMARKS
	Time (Zone)	Port Of Departure	Height Of Sea	Height Of Swell	Wind Velocity	Sea Temperature	Cargo Loss	
	Location	Bound To	Direction Of Sea	Direction Of Swell	Gusty	Air Temperature	Ship Heading	
7	20 April 1978	North Atlantic	Very Rough	Partly Cloudy	N x E	10 Miles	$96 K	"Typical Storm In North Atlantic Ocean."
	1255 (+2)	Philadelphia, PA	30 FT	29 FT	Force 10 (48-55 KN)	60°F	$0 K	
	41-05N, 37-25W	Rotterdam, Neth	N x E	N x E	?	?	?	
8	16 Dec 1971	Pacific Ocean	Very High N'ly Sea	Overcast, Rain	North	7 Miles	Unknown	Time / Wind D / F / Baro 0200 / N x W / 8-9 / 29.60 0400 / N / 9 / 29.42 0600 / ENE / 9 / 29.57 0800 / ENE / 9 / 29.72 1000 / E / 9 / 29.77 1200 / E / 8-9 / 29.73 1400 / ENE / 8 / 29.74 1600 / ENE / 8 / 29.78
	1435 (+11)	San Francisco, Calif.	30 FT	35 FT	45 KN	72°F	Unknown	
	30.6N, 165.5W	Yokohama, Japan	Northerly	Northerly	Yes	57°F	020° Gyro	
9	8 Dec 1971	Pacific Ocean	Rough	Squalls	Northerly	?	$100 K	
	0200 (+12)	San Francisco, Calif.	50 FT	50 FT +	55 KN	?	?	
	27-17N, 171-40W	Semarang, Indonesia	Northerly	Northerly	Yes	?	?	
10	16 July 1973	Arabian Sea	Very Rough	Fog, Rain	SW	7 Miles	$60 K	"Bulkhead Between #5 And #6 Port Wing Tank Together With Stiffeners Over An Area Of 25 Ft x 10 Ft . . . Centerline Girder And After Bracket At Bulkhead Between #5 And #6 Center Tanks Fractured For A Distance Of 6 Feet.'
	1622 (-3)	Rastamura, S. Arabia	20-30 FT	20-30 FT	Force 9 (41-47 KN)	77°F	None	
	16N 57E (Approx.)	Houston, Texas	Southwesterly	Southwesterly	Yes	77°F	?	
11	24 Dec 1974	Pacific Ocean	Heavy Seas	Heavy Seas	WSW	Overcast Code 5-7	$5.5 K	Wind Velocity Reported Probably Refers To Force 7-10 (28-55 KN)
	1525 (+9)	Seattle, Washington	20-30 FT	6 FT	7-10	37°F	–	
	42-42N, 152-00E	Yokohama, Japan	WSW	WSW	Yes	37/33°F	?	
12	19 Nov 1973	North Sea	Heavy Seas	Squally	NW	2 Miles	$120 K	"Six Anchor Lines Broke Due To Heavy Weather. Pipe Hangers On Riser To Keel Cooler And Vent Pipe."
	0902 (0)	–	20 FT	50 FT	65-75 Gust 86	N.A.	$81 K	
	56-11N, 02-47E	–	NW	NW	Yes	44°F	–	

TABLE A-1 (Continued)

REFERENCE NUMBER	COAST GUARD CASE NUMBER	VESSEL TYPE / VESSEL NAME	YEAR BUILT / OFFICIAL NUMBER	LENGTH / DRAFT FWD/AFT	GROSS TONNAGE / TYPE CARGO	DESCRIPTION OF CASUALTY
13	41452	Freighter	1967	694 Ft 03 In	24,471 Tons	While responding to M. S. MEXICAN TRADER"... took series of 53° rolls causing approx. 200 ton deck cargo to slide overboard causing damage to ship's hull... Sea water also entered thru forward hatches..." "Vessel called off assistance to distress and hove to for safety and self preservation to life, ship and cargo."
		GTS ADM. WM. CALLAGHAN	511744	25 Ft/26 FT	Military	
14	51559	Freighter (Container)	1969	602 Feet LOA	11,757 Tons	"3 containers and contents damaged and 3 (40 ft) containers lost overboard; #4 hatch. Deep web frame #23 and #27 cracked and distorted - main deck set down from weight of water...."
		S.S. RED JACKET	522650	30 Ft/32 Ft	*Containers*	
15	63230	Freighter	1969	605 Feet LOA	15,949 Tons	"1733 hours: There was a sharp loud crack, heard throughout the vessel... A fracture in the main deck port side of #4 hatch was sighted from the bridge deck.... approx. 16 feet in length."
		S.S. AMERICAN MAIL	521866	34 Ft/35 Ft	Grain/General	
16	03851	Freighter	1969	605 Feet	15,949 Tons	"... At 0300 we were suddenly lifted by a huge swell, rolling us to 35° starboard. This motion carried away lashing gear on after end of containers on hatch tops 2, 3, 4 and they began to slide back and forth ..."
		S.S. PRESIDENT WILSON	520392	27 Ft/36 Ft	General	
17	32036	Tanker	1969	632.3 Ft (Reg)	20,879 Tons	"... at about 1200 hours on 10 Feb 1973... Speed reduced to steerageway and vessel lay to head to seas. At 1912 hours a very heavy swell broke over stern from both sides flooding emergency generator room ...."
		S.S. OVERSEAS VIVIAN	518125	34 Ft/38 Ft	Bulk Heating Oil and Gasoline	
18	41881	RO-RO	1970	700 Feet LOA	15,131 Tons	"One trailer went overboard in heavy weather."
		S.S. ERIC K. HOLZER	530007	25 Ft/27 Ft	N.A.	

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TABLE A-1 (Continued)

Reference Number	Date / Time (Zone) / Location	Body of Water / Port Of Departure / Bound To	Sea Condition / Height Of Sea / Direction Of Sea	Weather Condition / Height Of Swell / Direction Of Swell	Wind Direction / Wind Velocity / Gusty	Visibility / Sea Temperature / Air Temperature	Repair Cost / Cargo Loss / Ship Heading	REMARKS
13	20 Dec 1973	North Atlantic	Mountainous	Overcast, Heavy Spray Overall	N To NW'ly	2 Miles	\$150 K	Same Storm And Approximate Ocean Area As S.S. SEALAND McLEAN When It Recorded Extreme Hull Girder Bending Stresses
	0500 GMT	Bremmerhaven, W. Ger	Over 40 FT	Over 40 FT	10-12 (48-55, 64° →)	52°F	\$500 K	
	47-30N, 15-40W	New York, N.Y.	Confused N'ly	Confused N'ly	Yes	48°F	?	
14	25 March 1974	Pacific Ocean	Very Rough	Overcast	W x N	5 Miles	\$52 K	"Vessel Length (602 FT) And Swells Were So Near The Same Length Vessel Completely Synchronized With The Swells . . ."
	0820 (+12)	New York, N.Y.	50 FT	50 FT	65-70 KN	?	\$18 K	
	37-10N, 175-50E	Yokohama, Japan	Westerly	Westerly	Yes	?	?	
15	7 Feb 1976	Pacific Ocean	Mountainous	Overcast, Snow	NNW	1/2 Mile	\$50 K	Vessel Speed Of 16.5 Knots Considered Excessive (By USCG) For Prevailing Sea Conditions.
	0733 GMT	Seattle, Washington	20-40 FT	20 FT	40-60 KN	33°F	\$180 K	
	46°54'N, 157°11'E	Yokohama, Japan	NNW	NNW	Yes	33°F	225° T	
16	13 March 1980	Eastern Pacific Ocean	High Sea	Overcast	WSW	10 Nautical Miles	\$280 K	Damage: "Coaming At #2 Carried Away. 5 Containers Lost Overboard. 27 Containers Damaged. 5 Cargo Booms Bent. 3 Hatch Covers Dented (1 Holed). . . . ."
	0300 (+8)	Oakland, California	20 FT	40 FT	22-27 KN	51°F	\$50 K	
	43°22'N, 126°15'W	Dutch Harbor, Alaska	WSW	WNW	No	53°F	?	
17	10 Feb 1973	Atlantic Ocean	Very Rough	Overcast, Rain	NNE	1-5 Miles	\$50 K	
	1912 (+5)	Houston, Texas	40 FT	40 FT	60-80 KN	70°F	\$0 K	
	35-41N, 74-47 W	Boston, Mass.	NNE	NNE	Yes	48°F	Head To Seas	
18	20 Feb 1974	Atlantic Ocean	Rough	Overcast	WSW	6 Miles	\$3 K	
	0745 EDST	New York, N.Y.	10 FT	6 FT	25 KN	72°F	\$10 K	
	36.7 N, 72.0 W	San Juan, P. Rico	WNW	Average	Yes	65°F	?	

TABLE A-1 (Continued)

REFERENCE NUMBER	COAST GUARD CASE NUMBER	VESSEL TYPE / VESSEL NAME	YEAR BUILT / OFFICIAL NUMBER	LENGTH / DRAFT FWD/AFT	GROSS TONNAGE / TYPE CARGO	DESCRIPTION OF CASUALTY
19	41427	Freighter (Van Carrier)	Rebuilt 1971	667 Feet	16,518 Tons	"Heavy weather damages encountered, heavy weather in Northwest Pacific Ocean shipping heavy seas over bow." "Watertight door on focs'le head sprung open." (dogs failed - door failure resulted in flooding of bow thruster room).
		S.S. JAPAN MAIL	287976	31 Ft/33 Ft	Containers - General	
20	42312	Freight	1971	720 Feet LOA	24,774 Tons	"Beam swells boarded at unknown time damaging 4 cargo containers."
		S.S. SEALAND ECONOMY	532410	29 Ft/32 Ft	Containers	
21	22094	Lash - Freight	1971	820 Feet	26,456 Tons	". . .SE swell apparently hit hull side sending water up under bridge wing in sufficient amount and force to buckle wing upward . . " "Prior to this time ship had been riding easily, seas and swells not large, *I would call this a 'Freak' sea*."
		S.S. GOLDEN BEAR	530138	30 Ft/31 Ft	Containers and Barges	
22	31427	Freighter (Lash)	1971	820 Feet	26,456 Tons	"Vessel proceeding on a course of 270° at a reduced speed (80 RPM) approx. 16 knots, *when struck by mountainous freak sea on* starboard bow."
		S.S. PACIFIC BEAR	530139	35 Ft/32 Ft	Barges and Containers	
23	41720	Freighter	1971	820 Feet	26,456 Tons	"Heavy sea broke over the bow, damaging the two forward winches, two stores cranes broke forward anchor light staff, broke loose four barge extenters (4 tons each) which in turn broke a small hatch leading to crews quarters. Water poured down damaged passageways. ."
		S.S. LASH TURKYIE	530143	26 Ft/31 Ft	General	
24	42751	Freighter (Lash)	1972	738.5 Ft (Reg)	26 156 Tons	"0830 informed by reefer maintenance several containers loose on deck. On investigation discovered 6 containers from slot 73 to 76 on port side had been stove in by a sea and several lashings parted, ... "
		S.S. JAPAN BEAR	530140	32 Ft/36 Ft	General and Reefer	
25	82485	Freighter	1972	875 Feet	21,668 Tons	"Damage caused by taking heavy seas over stern of vessel." "Damage to makeup rails and extensive damage to the motors of the port and starboard transporters due to salt water."
		S.S. DOCTOR LYKES	536500	34 Ft/37 Ft	General	

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TABLE A-1 (Continued)

Reference Number	Date / Time (Zone) / Location	Body of Water / Port Of Departure / Bound To	Sea Condition / Height Of Sea / Direction Of Sea	Weather Condition / Height Of Swell / Direction Of Swell	Wind Direction / Wind Velocity / Gusty	Visibility / Sea Temperature / Air Temperature	Repair Cost / Cargo Loss / Ship Heading	REMARKS
19	15 Dec 1973	NW Pacific Ocean	Very Rough	Heavy Seas	WSW'ly	5 Miles	$80 K	Damage Occurred At Night
	? (-10)	Seattle, Washington	12-20 FT	20-30 FT	35-40 KN	38°F	$0 K	
	48°N, 165°E	Yokohama, Japan	WSW	WSW'ly	Yes	35°F	?	
20	5-6 March 1974	Atlantic Ocean	Very Rough	Overcast, Rain	NW	5 Miles	$0 K	Damage Occurred At Night
	? (+1)	Rotterdam, Neth	20 FT	30 FT	55 KN	57°F	$2.1 K	
	39N, 29W	Houston, Texas	NW	NW	Yes	45°F	?	
21	27 Feb 1972	North Pacific Ocean	Mod. To Heavy SE Swell	Overcast	SSW	10 Miles	$90 K	Wind Velocity May Correspond To Force 5 (19-24 Knots) "Location Of Wing Over Forward Part Of Ship, 100 Aft Of Bow Cannot Escape Injury As Time Goes On . . . . ."
	1132 (-9)	Yokohama, Japan	6 FT	12 FT	5	57°F	$0 K	
	34-46N, 140-28E	San Francisco, Calif.	SSW	SE	No	56/57°F	090° True	
22	17 Jan 1973	North Pacific Ocean	Rough	Overcast	W x S	5 Miles	$5 K	Starboard Wing Bridge . . . Wavy And Distorted . . . . Fractured After Bulkhead In Chief Officers Quarters
	2012 (+9)	San Francisco, Calif.	12 FT	20 FT	45 KN	62°F	$0 K	
	32-21N, 137-55W	Yokohama, Japan	West	West	Yes	53°F	270° True	
23	6 Feb 1974	Atlantic Ocean	Very Rough And High Swells	Overcast, Rain	WNW'ly	About 5 Miles	$100 K (Approx)	Ship Eventually Turned And Ran Before Storm.
	0430 (+3)	Cadiz, Spain	40-50 FT Swells	40-50 FT	Over 60 KN	58°F	Unknown	
	39N, 59W	New York, N.Y.	WNW'ly	WNW'ly	Yes	60°F	Hove To Into Sea	
24	21 Jan 1974	Pacific Ocean	Rough	Rain	170°	Four Miles	$1 K	Time / Wind Dir / Speed: 0100 180 46; 0200 180 46; 0300 172 60; 0400 168 46; 0500 170 44; 0600 185 43
	Approximately 0500 (+11)	San Francisco, Calif.	12 FT	12 FT	44 KN	54°F	$20 K	
	39-08N, 159-15W (Approx.)	Yokohama, Japan	170°	180°	Yes	59°F	300° Gyro	
25	21 Feb 1978	Atlantic Ocean	Very High	Overcast, Rain	W x N	2.5 Miles	$150 K	
	1800-2100 (+1)	Newport News, VA.	30 FT	41 FT	Over 70 MPH	60°F	$0 K	
	39-54N, 35-19W	Rotterdam, Neth	NW'ly	NW'ly	No	50°F	?	

TABLE A-1 (Continued)

REFERENCE NUMBER	COAST GUARD CASE NUMBER	VESSEL TYPE / VESSEL NAME	YEAR BUILT / OFFICIAL NUMBER	LENGTH / DRAFT FWD/AFT	GROSS TONNAGE / TYPE CARGO	DESCRIPTION OF CASUALTY
26	41688	Freight, Container	1972	892 Feet	41,127 Tons	"At 1450 hours, local time on a course of 075°, winds NW'ly force 10-12, high seas, vessel took a sudden heavy roll to starboard and shipped a green sea on the starboard side main deck between cells 7 & 9 extending to the 01 level on the starboard side. This sea was taken on the leeside."
		S.S. SEALAND McLEAN	540413	30 Ft/33 Ft	General	
27	61999	Container Ship	1972	892 Feet	41,127 Tons	"On course 255°. Speed 18 knots. Rough NW'ly seas and heavy confused to WNW'ly swell. Vessel riding fair, deep. W'ly swell picked up forward part of vessel and dropped into trough when breaking WNW sea came across bow, resulting in damage indicated."
		S.S. SEALAND McLEAN	540413	33 Ft/35 Ft	General, Containers	
28	72394	Container/Freight	1972	892 Feet	41,127 Tons	"Sometime between 2000 3/7 and 0800 3/8 sustained heavy weather damage to shell plating while pitching heavily at times in very heavy seas and swells. Crack on port and stb'd deck doubler on forward corner #1 container hatch."
		S.S. SEALAND GALLOWAY	542200	30 Ft/34 Ft	General in Containers	
29	82861	Freight/Container	1972	892 Feet	41,127 Tons	"0119 R/S to 70 RPM (15) kts wind SW to WSW 8-9 rough seas, overcast. Vessel riding fair, taking frequent heavy spray from port bow with occasional labor. At 0332 vessel pitched heavy to port taking very heavy spray and then dived heavy to starboard resulting in damage as listed below: Broke out second in-board starboard pilot house window, sprung frame on two window frames on 02 level and one window on 01 level stb'd side - bent anchor lt. stanchon on fore deck, bent bulwark inboard port side adjacent to #1/2 hatches (aft 4 ft in length). . . ."
		S.S. SEALAND McLEAN	540413	34 Ft/34 Ft	General Container	

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TABLE A-1 (Continued)

Reference Number	Date / Time (Zone) / Location	Body of Water / Port Of Departure / Bound To	Sea Condition / Height Of Sea / Direction Of Sea	Weather Condition / Height Of Swell / Direction Of Swell	Wind Direction / Wind Velocity / Gusty	Visibility / Sea Temperature / Air Temperature	Repair Cost / Cargo Loss / Ship Heading	REMARKS
26	15 Feb 1974	Atlantic Ocean	High	Mostly Cloudy	NW'ly	5-10 Miles	$40 K (Approx)	"This Green Sea Carried Away The No. 1 Lifeboat Damaging The Stb'd Gangway And Controls. Containers In Position 898 And 998, Smashing 2 Doors On The Stb'd Side Of 01 Level"
	1520 (0)	Port Elizabeth, N.J.	20-25 FT	20-25 FT	60 KN	51°F	$30 K (Approx)	
	47-31N, 19-58W	Rotterdam, Neth	NW'ly	NW'ly	Yes	50°F	075° True	
27	15 March 1976	Pacific Ocean	Rough	Overcast	NW	7 Miles	$50 K	"Slight Buckle In Foredeck In Way Of Frames 353 To 359. . . .Access Manhole to 1 Cargo Hold Damaged."
	1409 (+10)	San Francisco, Calif.	18-20 FT	20 FT	40-45 KN	61°F	$0 K	
	35-43N, 151-06W	Yokohama, Japan	NW	Confused To WNW	Yes	55°F	255°	
28	7-8 March 1977	North Atlantic	Very Rough	Overcast	SSW To WNW	5 Miles	Unknown	Damage Appears Inconsistent With Prevailing Winds And Seas
	2000-0800 (+1 To +2)	Algeciras, Spain	8-12 FT	13-20 FT	30-40 KN	54-57°F	$0 K	
	41.6°N, 28.6°W (Approx)	Elizabeth, N.J.	WNW To NW	W x N To NW	Yes	50-53°F	?	
29	5 Dec 1977	Pacific Ocean	Rough	Overcast	SW To WSW	3-5 Miles	$50 K	Damage Appears Inconsistent With Prevailing Winds And Seas
	0332 GMT	San Francisco, Calif.	15-20 FT	10-12 FT	45-50 KN	47°F	$0 K	
	44°56'N, 149°15'W	Yokohama, Japan	WSW	WSW	Yes	?	?	

TABLE A-1 (Continued)

REFERENCE NUMBER	COAST GUARD CASE NUMBER	VESSEL TYPE	YEAR BUILT	LENGTH	GROSS TONNAGE	DESCRIPTION OF CASUALTY
		VESSEL NAME	OFFICIAL NUMBER	DRAFT FWD/AFT	TYPE CARGO	
30	51546	Freight/Container	1972	946 Feet LOA	41,127 Tons	"At 0300 hours on course 285°, speed 15 kts with vessel working moderately, vessel took unexpected sea over port bow. Fore deck dished in approximately 10 to 12 inches. Port bridge wing buckled back approximately 8 in. Three windows on forward side of forward house and two dislodged."
		S.S. SEALAND McLEAN	540413	34 Ft/34 Ft	General Container	
31	61659	Container Freight	1973	892 Feet	41,127 Tons	"The vessel encountered extremely rough seas and heavy swells during the early morning hrs of February 3rd, 1976. The damage to the vessel was the result of shipping a sea on the port side between frames #255 and #275. The damage sustained includes a hairline crack in the main deck, 14 inches in length at Frame #274 on the port side by the forward end of No. 2 hatch, and damage to the bulwark on the port side which was stove in between Frame #259 and #273."
		S.S. SEALAND MARKET	550721	30 Ft/32 Ft	Containers	
32	41432	Container	1973	946 Feet	41,127 Tons	"1450 vessel encountered mountainous swell, shipped heavy seas over focs'le head from a direction of approx. 15° on the port bow. . . In ship's office, port bent out, office flooded. Rooms #31, #32 on 01 level, windows broken, rooms flooded. Room #33 window bent at hinges some salt water damage. Room 13 at 02 level two windows bent at hinges some salt water damage. . . ."
		S.S. SEALAND MARKET	550721	34 Ft/35 Ft	General Container	

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TABLE A-1 (Continued)

Reference Number	Date / Time (Zone) / Location	Body of Water / Port Of Departure / Bound To	Sea Condition / Height Of Sea / Direction Of Sea	Weather Condition / Height Of Swell / Direction Of Swell	Wind Direction / Wind Velocity / Gusty	Visibility / Sea Temperature / Air Temperature	Repair Cost / Cargo Loss / Ship Heading	REMARKS
30	30 Nov 1974	North Atlantic Ocean	Very Rough	Broken Cloud	SSW	8 Miles	\$50 K	
	0330 (+2)	Bremerhaven, W. Ger	25-30 FT	15-30 FT	50 KN	41°F	Unknown	
	45°21'N, 44°10'W	New York, N.Y.	220°	210-220°F	Yes	42°F	285° True	
31	3 Feb 1976	Atlantic Ocean	Very Rough	Overcast	WSW	8 Miles	\$18 K	
	0200 (+5)	Rotterdam, Neth	40 FT	50 FT	60 KN	31°F	\$0 K	
	44°N, 57°W	Elizabeth, N.J.	WSW	WSW	Yes	27°F	?	
32	16 Jan 1974	Atlantic Ocean	△1	Overcast	△1	△1	\$50 K	Note: △1 Information Given In Deck Log Abstract Of Figure A-1. 600 Ft^2 Of Foredeck Set Down About 2 Inches.
	1450 (-1)	Bremerhaven, W. Ger	△1	△1	△1	?	?	
	50°05'N, 03°42'W	New York, N.Y.	△1	△1	△1	?	△1	

TABLE A-1 (Continued)

REFERENCE NUMBER	COAST GUARD CASE NUMBER	VESSEL TYPE / VESSEL NAME	YEAR BUILT / OFFICIAL NUMBER	LENGTH / DRAFT FWD/AFT	GROSS TONNAGE / TYPE CARGO	DESCRIPTION OF CASUALTY
33	51755	Container	1973	946 Feet	41,127 Tons	"On the morning of Nov 26, 1974 vessel encountered heavy seas and swells. Various courses and speeds were used to minimize pitching but the below damage occurred in spite of the actions taken: 1. Buckling of shell plating on the port side in way of frame 320 extending from forecastle deck down to 01 lower hold. Deflection approx. 1 inch from the norm. 2. Buckling of forecastle deck plating approx. 10 feet from stern indentation about 3-1/2 inches. 3. Tear in breakwater where it joins the deck, approx. 21 inch tear. 4. Three windows sprung."
		S.S. SEALAND EXCHANGE	546383	33 Ft/33 Ft	General in Container	
34	90697	Container, Freight	1973	669 Feet	21,467 Tons	"During the periods of heavy weather, vessel shipped continuous green seas over the bows, at times with a racking stress. The bow thruster room was flooded to the 10 ft level, firemain in the box girder fractured, two containers were stove in . . . . , fire station #8 door was torn from the hinges, ..."
		S.S. PRESIDENT JEFFERSON	544900	27 Ft/33 Ft	Containers	
35	61029	Lash/Freighter	1974	811.7 Feet	32,269 Tons	"Vessel's bow dropped into trough of sea, crest struck starboard bridge wing extension. Bridge wing bent about 20°, welded fittings torn and opening in side of house made over area of about 4 feet."
		S.S. STONEWALL JACKSON	557034	32 Ft/36 Ft	General	
36	61536	Lash/Freighter	1974	811.7 Feet	32,269 Tons	"Vessel proceeding to New York encountered extremely heavy weather. Vessel was eased & manuevered as best possible but due to mountainous seas caused by occasionally confused seas coming together the following major items of damage were found. Port gangway was torn loose and thrown on deck, starboard aft lifting pad of crane swiveled severing electrical and hydraulic fittings, Jack staff bent."
		S.S. ROBERT E. LEE	557033	31 Ft/31 Ft	Jute Products in Barges	

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Reference Number	Date / Time (Zone) / Location	Body of Water / Port Of Departure / Bound To	Sea Condition / Height Of Sea / Direction Of Sea	Weather Condition / Height Of Swell / Direction Of Swell	Wind Direction / Wind Velocity / Gusty	Visibility / Sea Temperature / Air Temperature	Repair Cost / Cargo Loss / Ship Heading	REMARKS
33	26 Nov 1974	North Pacific	Rough	Overcast	West	6-10 Miles	$16.6 K	
	1330 (+11) (Approx)	Oakland, California	20-30 FT	40-50 FT	40-50 KN	58°F	?	
	36°30'N, 163°45'W	Yokohama, Japan	Westerly	Westerly	Yes	53°F	?	
34	5 Dec 1978	Pacific Ocean	Precipitous	Heavy Spray	240° True	1-2 Miles	$60 K	
	0800-1600 (-10) (Local)	Seattle, Washington	35-60 FT	18 FT	70-90 KN	38°F	$8 K	
	BTN. 45°17'N, 155°23'E And 44°38'N, 153°03'E	Yokohama, Japan	240° True	180° True	Yes	44°F	?	
35	22 Dec 1975	Atlantic Ocean	Very Rough	Overcast	Southeasterly	5-8 Miles	$500K ⚠1	"Master's Living Quarters Flooded." "Life Saving Equipment Became Unsatisfactory As A Result Of This Casualty." 12 Liferings Lost, Inflatable Life Raft Deployed On Deck. Note: ⚠1 Entry Blurred.
	BTN 0400 & 1500 (+4)	New York, N.Y.	20-30 FT	20-30 FT	30-50 KN	66°F	$0 K	
	39°42'N, 61°42'W	Near East Ports Via Suez Canal	SE'ly Confused	SE'ly Confused	Yes	60°F	?	
36	18 Jan 1976	North Atlantic	Mountainous Seas	Overcast, Rain	SSW To NW	1-5 Miles	$15 K	
	0500-1600 (+5)	From Jeddah Via Suez Canal	25 FT	Occassionally 50 FT	50-70 KN	52°F	$0 K	
	40°12'N, 59°14'W (Noon Position)	New York, N.Y.	S-SW	S-SSW-W'ly	Yes	54°F	?	

TABLE A-1 (Continued)

REFERENCE NUMBER	COAST GUARD CASE NUMBER	VESSEL TYPE / VESSEL NAME	YEAR BUILT / OFFICIAL NUMBER	LENGTH / DRAFT FWD/AFT	GROSS TONNAGE / TYPE CARGO	DESCRIPTION OF CASUALTY
37	03853	Tanker	1976	894 Feet LOA	44,875 Tons	"Enroute to Küre, Japan vessel was about 750 miles SW of center of Typhoon Tip. About 2100 hours vessel dived into a sea head on, shuddered and foremast light went out. At daylight it was observed that foremast had been knocked down to main deck."
		S.S. BEAVER STATE	572359	46 Ft/49 Ft	Crude Oil	
38	90984	Tanker	1978	869 Feet	60,384 Tons	"Increasing winds and seas while clearing Wessel Shoal to gain sea room. Two hull plates on starboard bow above main deck were set in and the interior framing set in."
		S.S. TONSINA	585629	50 Ft/55 Ft	Prudhoe Bay Crude	

Note:
Table
Continued on
Next Page

TABLE A-1 (Continued)

Reference Number	Date / Time (Zone) / Location	Body of Water / Port Of Departure / Bound To	Sea Condition / Height Of Sea / Direction Of Sea	Weather Condition / Height Of Swell / Direction Of Swell	Wind Direction / Wind Velocity / Gusty	Visibility / Sea Temperature / Air Temperature	Repair Cost / Cargo Loss / Ship Heading	REMARKS
37	18 Oct 1979	Luzon Strait	Rough	Overcast	Easterly	10 Miles	$75 K	Repair Cost Appears Inconsistent With Description Of Damage
	2100 Local (-8 Hours)	Rastamura, S. Arabia	15 FT	15 FT	35 KN	80°F	$0 K	
	21°53'N, 121°05'E	Kiire, Japan	NE	Confused	No	79°F	?	
38	22-23 Dec 1978	Gulf Of Alaska	Very Rough	Overcast	SW To W	Moderate To Good	$50 K	
	(Night)	Valdez, Alaska	25 FT	30 FT	Force 9 (34-40 KN)	44°F	?	
	BTN Cape Hinchinbrook & Cape St. Elias	Parita Bay, Panama	Westerly	Southwesterly	Yes	36°F	?	

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LOADS ADVISORY GROUP

The Loads Advisory Group prepared the project prospectus and evaluated the proposals for this project.

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PROJECT ADVISORY COMMITTEE

The SR-1281 Project Advisory Committee provided the technical guidance, and reviewed the project reports with the investigator.

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SSC-308, Criteria for Hull-Machinery Rigidity Compatibility by W.I. H. Budd, S. V. Karve, J. G. de Oliveira, and P. C. Xirouchakis. 1981. AD-A117056

SSC-309, A Rationale Basis for the Selection of Ice Strengthening Criteria for Ships - Vol. I by J. L. Coburn, F. W. DeBord, J. B. Montgomery, A. M. Nawwar, and K. E. Dane. 1981. AD-A120601

SSC-310, A Rational Basis for the Selection of Ice Strengthening Criteria for Ships - Vol. II - Appendices by J. L. Coburn, F. W. DeBord, J. B. Montgomery, A. M. Nawwar, and K. E. Dane. 1981. AD-A120602

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SSC-315, Fatigue Considerations in View of Measured Load Spectrum by W. G. Dobson, R. F. Broderick, J. W. Wheaton, J. G. Giannotti, and K. A. Stambaugh. 1982

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